Utility gains from reductions in the modifiable burden of lung cancer attributable to residential radon in Canada

Janet Gaskin¹ · Doug Coyle¹ · Jeff Whyte² · Dan Krewski¹

Received: 7 November 2017 / Accepted: 5 August 2018 / Published online: 27 September 2018
© The Canadian Public Health Association 2018

Abstract

Research question The objective of this analysis is to estimate the modifiable burden of disease according to the annual number of lung cancer deaths prevented and the associated period gain in quality-adjusted life years (QALYs) for the 2012 populations in Canada from reductions in residential radon exposures.

Interventions Two postulated interventions for residential radon mitigation in new construction are assessed, corresponding to a 50% reduction and an 85% reduction in radon nationally, in the provinces/territories, and in 17 census metropolitan areas in Canada.

Methods Data were derived from two recent Canadian radon surveys conducted by the Radiation Protection Bureau, Health Canada, along with Canadian mortality and quality of life data. Analyses adopted a lifetime horizon and a discount rate of 1.5%. A period life-table analysis was conducted using age- and sex-specific all-cause and lung cancer mortality rates, adjusted for smoking, and the BEIR VI exposure-age-concentration model for radon-attributable risk of lung cancer mortality.

Results A reduction in residential radon by 50% could prevent 681 lung cancer deaths, associated with a gain of 15,445 QALYs in the Canadian population at a discount rate of 1.5%; a reduction in radon by 85% could prevent 1263 lung cancer deaths, associated with a gain of 26,336 QALYs. On a per population basis, the Yukon was estimated to benefit most from radon mitigation.

Conclusion The magnitude of QALY gains in Canada estimated under the two radon mitigation scenarios is appreciable but varies considerably across provinces due to variability in indoor radon concentrations and smoking rates.

Résumé

Objectif Cette analyse a pour objectif d'estimer la charge modifiable des maladies en tant que le nombre évitable de décès de cancer du poumon attribué au radon et l'accroissement des années de vie ajustées sur la qualité (AVAQ, que l'anglais appelle QALY) à la suite des réductions potentielles de l'exposition au radon subie par la population du Canada en 2012.

Interventions Les effets de deux interventions qui pourraient être intégrées dans la construction de tous nouveaux logements pour réduire l'exposition au radon domestique, qui correspondraient à des réductions de 50 % et de 85 %, sont estimés pour la population du Canada, de chaque province et territoire, et de 17 régions métropolitaines de recensement.

Méthode Les données relevées par deux enquêtes récentes mesurant la concentration de radon domestique menées par le Bureau de la protection contre les rayonnements des produits cliniques et de consommation de Santé Canada, ainsi que les données pour le taux de mortalité et la qualité de vie selon le groupe d'âge et le sexe fournies par Statistique Canada. L'analyse adopte l'horizon temporel de la vie entière et la valeur des années futures est actualisée à un taux de 1,5 %. L'analyse des tables de survie par période repose sur les tables de mortalité toutes causes et du cancer du poumon selon

✉ Janet Gaskin
jgaskin@uottawa.ca

¹ School of Epidemiology and Public Health, University of Ottawa,
Room 101, 600 Peter Morand Crescent, Ottawa, ON K1G 5Z3,
Canada

² Construction Research Centre, National Research Council, 1200
Montreal Rd, Ottawa, Canada

le sexe et le groupe d'âge, portant sur les fumeurs, les non-fumeurs et agrégées, et le modèle âge-période-concentration proposé par le BEIR VI pour le risque de mortalité par cancer de poumon attribuable au radon.

Résultats 681 décès par cancer du poumon pourraient être évités par une réduction de radon domestique de 50 %, ce qui entraîne un accroissement de 15 445 AVAQ pour la population du Canada à un taux de 1,5 % pour la valeur des années futures; 1263 décès par cancer du poumon pourraient être évités par une réduction de radon domestique de 85 %, ce qui entraîne un accroissement de 26 336 AVAQ. La réduction de radon domestique fournit les meilleurs avantages par habitant pour le Yukon.

Conclusion L'ampleur des gains en AVAQ à la suite des réductions potentielles de l'exposition au radon domestique pour la population du Canada est appréciable, et montre une variation considérable parmi les provinces et les régions métropolitaines de recensement, selon la distribution de radon domestique et le taux de tabagisme.

Keywords Radon · Exposure mitigation · Lung cancer · Quality-adjusted life years · Life tables

Mots-clés Radon · Exposition domestique · Cancer du poumon · Années de vie ajustées sur la qualité · Tables de survie

Introduction

Radon is a naturally occurring radioactive gas that was identified as a human carcinogen by the International Agency for Research on Cancer (IARC) in 1988 (Dunn and Cooper 2014). Radon is produced when uranium-238 in the ground undergoes radioactive decay, and can collect in houses after entering from the surrounding soil via various entry points (such as cracks in concrete and gaps around service pipes). Following inhalation of radon gas and some short-lived radon progeny, the alpha particles emitted in radioactive decay can damage cellular deoxyribonucleic acid (DNA) in the lung tissue. Radon is an important and modifiable cause of lung cancer, second only to smoking.

In Canada, lung cancer is the second most common cancer (accounting for 14% of all cancers among men and women combined). Lung cancer has the highest mortality rate, with 27% of all cancer deaths attributable to lung cancer for men and women combined (Canadian Cancer Society et al. 2014). Ranked second only to ischemic heart disease among causes of premature death in Canada in 2010, it was estimated that 354,000 years of life were lost to lung cancer, representing an increase of 21% from 1990 (IHME 2013).

The burden of disease from residential radon in Canada has been assessed in terms of population attributable risk (PAR) for lung cancer mortality. The PAR of lung cancer for residential radon in Canada has recently been estimated to be 16% (Chen et al. 2012), with the PAR in Ontario estimated at 13.6% (Peterson et al. 2013). A range of models for excess relative risk and for the residential radon distribution in Canada were evaluated recently (Al-arydah 2017), with PAR reported as ranging from 11.9% to 19.4% for male ever-smokers, from 12.6% to 20.4% for female ever-smokers, from 19.6% to 41.8% for male never-smokers, and from 19.5% to 44.3% for female never-smokers. The burden in terms of PAR can only be reduced because it is only possible to reduce and not eliminate

residential radon. These studies have also estimated the cases of lung cancer that could be prevented in existing housing if residential radon exposures above a specific threshold were mitigated. The modifiable burden of lung cancer attributable to radon was evaluated according to DALY (disability-adjusted life year) gains from a theoretical reduction of above-threshold radon in existing housing for five provinces in Canada, with the largest potential DALY gains estimated for Quebec and Ontario (Al-arydah 2018).

This study evaluates a strategy to reduce population radon exposures using radon interventions that shift the entire distribution to lower radon concentrations to maximize the number of lung cancer cases prevented. Passive preventive measures installed at construction and active depressurization systems are the two interventions that have been implemented and evaluated for radon control in new construction. A recent review paper of radon control in new homes (Angell 2013) summarized studies of the installation and effectiveness of both passive preventive measures and active soil depressurization systems. It was estimated that 73% of lung cancer deaths attributable to residential radon in Ontario (Peterson et al. 2013) and 85% in the United Kingdom (Gray et al. 2009) would result from exposures below 100 Bq/m³.

Quality-adjusted life years (QALYs) have more recently been identified as the preferred metric for assessment of the health benefits of interventions in Canada by the Canadian Agency for Drugs and Technologies in Health (CADTH). QALYs use a preference-based assessment of the health-related quality of life, with a value between 1 for perfect health and 0 for death, for each life year gained. Health technology assessments in Canada increasingly report cost-effectiveness ratios (\$/QALY) to make health system decision-making more explicit and to improve transparency and public involvement (Jaswal 2013).

This analysis evaluates the burden of disease from radon-attributed lung cancer mortality in terms of QALYs that it would be possible to eliminate should current interventions for new housing be implemented across the population, assessed for Canada, each province and territory, and 17 census metropolitan areas. Different populations within Canada are included because radon in indoor air has been determined by the courts to be under areas of health and the environment and so under shared federal, provincial, and municipal jurisdiction (Dunn and Cooper 2014). This study also considers the relative risk of overall mortality and lung cancer mortality between current smokers, and former smokers according to time since quitting, compared to non-smokers. The changes in age-specific smoking status impact the model because current smoking rates peak between the ages of 20 and 35 years and then decrease while lung cancer mortality increases with age. Estimation of the modifiable burden of lung cancer in terms of QALYs per 100,000 population helps to identify populations that would benefit most from investment in radon prevention because both the QALYs gains and the costs of reducing residential radon vary with the population size.

Research question

The objective of this analysis is to estimate the modifiable burden of disease according to the annual number of lung cancer deaths prevented and the associated 5-year period gain in QALYs for the 2012 populations in Canada from two interventions to prevent radon entry into new construction applied to the population at the national level, for each province/territory, and for 17 census metropolitan areas (CMAs).

Methods

Target populations

The national and provincial/territorial populations from 2012 in Canada are modeled with replacement over the 100-year period of the analysis (Statistics Canada 2012b). The populations of the following 17 CMAs were derived from the 2011 Census data (Statistics Canada 2011a): St. John's (NL), Halifax (NS), St. John (NB), Quebec (QC), Sherbrooke (QC), Montreal (QC), Ottawa-Gatineau (NCR [National Capital Region]), Kingston (ON), Toronto (ON), Windsor (ON), Winnipeg (MB), Saskatoon (SK), Regina (SK), Edmonton (AB), Calgary (AB), Kelowna (BC), and Vancouver (BC).

Intervention strategies

The base scenario in this analysis is described by the current residential radon distribution determined in the representative national radon survey of 2009–2011 (Health Canada 2012). Two interventions to prevent radon entry into new construction are compared to the base scenario in this analysis: having passive preventive radon measures such as radon protective membrane and sealing joints and cracks in the floor and foundations, and second, depressurization with an active fan-powered system. The passive preventive measures typically yield about a 50% reduction in radon levels (Woolliscroft et al. 1994), determined from a comparison of radon levels in new construction with and without radon membranes installed for selected sites with high radon levels in Devon and Cornwall in the UK. An active (fan-powered) depressurization system was conservatively assumed to result in about an 85% reduction in radon levels, as reported from field trials in Denmark (Andersen et al. 1997). A recent summary of radon reduction in 52 houses after installation of active depressurization systems in Canada reported an average radon reduction of 91% (Health Canada 2016). This analysis considers the theoretical scenarios of population-wide radon reduction in the proportion of housing where occupants are exposed to radon (excluding upper-floor apartments/condos), listed in Table 1, to estimate the maximum potential benefit of these interventions (the modifiable radon burden).

Study perspective and time horizon

A societal perspective and a lifetime horizon were adopted for this study because residential radon exposure is lifelong, and lung cancer mortality in Canada peaks between age 75 and 89 years.

Discounting

The discount rate used for the base analysis is 1.5%, recommended by CADTH (2017). A discount rate of 0% is also used for comparison purposes.

Modeling

This abridged period life-table approach uses 5-year age intervals, and age- and sex-specific all-cause and lung cancer mortality rates calculated from the census and death database. The probabilities of death reported in the death database were first converted into mortality rates, so that an exposed person's risk can be modeled as the sum of the baseline risk and the risk due to radon exposure, expressed in terms of an intensity ratio. The probability of surviving to the beginning of each age interval, of dying during the age interval, and the intensity ratio between all-cause and lung cancer mortality are used to

Table 1 Radon distribution and radon-exposed housing occupancy for Canada, provinces, and cities

Canada, provinces, territories	Radon distribution		Housing occupancy % (radon exposed)	CMA	Radon distribution		Housing occupancy % (radon exposed)
	Geo mean	GSD			Geo mean	GSD	
Canada	41.7	2.64	86.7				
NL	32.8	2.94	96.9	St. John's, NL	62.5	2.34	95.3
NS	38.6	3.34	88.2	Halifax, NS	91.3	3.14	78.7
PEI	22.3	2.71	93.2				
NB	62.4	3.55	92.2	St. John, NB	70.8	2.74	87.0
QC	36.6	3.04	78.8	Quebec, QC	67.4	2.74	75.5
				Sherbrooke, QC	119.8	2.64	77.6
				Montreal, QC	69.4	2.54	71.0
ON	34.4	2.64	78.7	Ottawa-Gatineau, NCR	79.1	2.13	78.7
				Kingston, ON	123.2	2.03	80.7
				Toronto, ON	45.3	1.82	67.3
				Windsor, ON	122.5	1.72	86.3
MB	100.1	2.38	85.3	Winnipeg, MB	198.9	1.93	79.7
SK	88.0	2.23	90.9	Saskatoon, SK	138.5	1.38	85.0
				Regina, SK	240.8	1.93	87.0
AB	64.6	1.99	88.8	Edmonton, AB	96.2	1.72	86.7
				Calgary, AB	106.8	1.72	85.0
BC	25.5	2.06	78.2	Kelowna, BC	96.7	1.93	88.5
				Vancouver, BC	20.9	1.93	72.7
NU	8.60	1.19	93.4				
NT	39.4	2.93	89.9				
YT	85.7	2.88	94.2				

Geo mean geometric mean, *GSD* geometric standard deviation, *NCR* National Capital Region

determine baseline and exposed life expectancy (LE , LE_E) and lifetime risk (LR , LR_E) of lung cancer. The population attributable risk is calculated using Eq. 1 from the population-averaged lifetime risk in the exposed (LR_E) and the baseline lifetime risk for a theoretical unexposed population (LR) as described in Brand et al. (2005):

$$PAR = \frac{LR_E - LR}{LR_E} \quad (1)$$

Residential radon distribution

The indoor radon distributions for Canada, the provinces/territories, and CMAs are listed in Table 1, defined by the geometric mean and geometric standard deviation. The `fitdistrplus` function in R using population weights and the maximum likelihood estimator was used to determine the radon distributions from two recent Canadian radon surveys conducted by the Radiation Protection Bureau, Health Canada. The national and provincial/territorial radon distributions were determined from a representative national radon survey conducted between 2009 and 2011, based on 3-month-long measurements taken during the winter months

using passive alpha-track radon detectors from Track Analysis Systems Limited (Health Canada 2012). The radon distributions for the CMAs were determined from a second radon-thoron survey of 33 CMAs in Canada conducted in 2012–2013 (Chen et al. 2014). Residential radon data below the detection limit of 15 Bq/m^3 were approximated in this analysis by half that value, 7.5 Bq/m^3 .

All-cause and lung cancer mortality by smoking status

Current smoking data by sex- and age-specific category in Canada for 2012 (Table 2) used in this analysis were reported nationally and for each province and territory by the Canadian Community Health Survey (CCHS) (Statistics Canada 2013). All-cause mortality rates for 2012 were reported in the Death Database (Statistics Canada 2012a) by sex- and age-specific category in Canada, nationally and for each province and territory. Lung cancer mortality rates were assumed to constitute the same proportion of lung cancer incidence rates (Statistics Canada 2012c) as were reported in the National Cancer Institute SEER cancer statistics review for the US population between 1975 and 2009 (Howlander et al. 2012), based on similar patterns of high

mortality rates and low life expectancy post diagnosis in both countries. All-cause mortality (including lung cancer) and lung cancer mortality were both adjusted for smoking using the respective relative risk for smokers versus non-smokers by sex- and age-specific category (Villeneuve and Mao 1994). The values of relative risk of all-cause and lung cancer mortality for smokers versus non-smokers (RR_e) by sex and age category used were those reported by the American Cancer Society Cancer Prevention Study II (ACS CPS-II) (Thun et al. 1997). The CPS II relative risk by age and sex category are given for current (daily and occasional) versus lifelong non-smokers (Table 2). The population consists of former smokers in addition to current smokers and lifelong non-smokers. Based on more recent research estimating the relative risk of former smokers according to time since quitting, this analysis modeled smokers who quit more than 20 years prior as lifelong non-smokers, and assumed a linear decrease in relative risk over a 20-year period for former smokers (Kenfield et al. 2008; Pesch et al. 2012). Due to the small population sizes in the territories (the Yukon, the Northwest Territories and Nunavut), the all-cause and lung cancer mortality rates were averaged over the ten previous years, from 2003 to 2012.

Excess relative risk model for lung cancer mortality from radon exposure

The sixth committee on Biological Effects of Ionizing Radiation Exposure-Age-Concentration (BEIR VI EAC) model based on 11 miner cohorts (NRC 1999) is the most comprehensive radon risk projection model for estimating the age-specific excess rate ratio (excess relative risk per working level month (ERR/WLM)) in relation to cumulative radon exposure, including modifying factors for smoking status, effective exposure duration, exposure-rate effect, and attained age. A working level month is a cumulative exposure defined as breathing a concentration of 1 WL (2.08×10^{-5} J/m³) for a working month of 170 h (1 WLM = 6.37×10^5 Bq/m³ per hour for equilibrium equivalent concentration of radon, and assuming an equilibrium factor of 0.4 and 7000 h per year indoors at home, 1 Bq/m³ radon exposure for 1 year = 0.0044 WLM at home). The smoking adjustment factor for non-smokers is roughly double that for smokers, the attained age factor decreases with age, and the exposure-rate factor decreases with exposure rate. The effective exposure duration (η_i) is calculated using three weighted periods that exclude the 5 years prior to

Table 2 Age-specific HUI and age- and sex-specific RR for all-cause mortality and RR for lung cancer mortality

Age group (years)	HUI mean (SD)	RR all-cause mortality M	RR all-cause mortality F	RR lung cancer mortality M	RR lung cancer mortality F	Canada: current smoker, daily or occasional M Mean (95% CI)	Canada: current smoker, daily or occasional F Mean (95% CI)
0–4	0.910 (0.140)	1.0	1.0	1.0	1.0	0 (0, 0)	0 (0, 0)
5–9	0.910 (0.140)	1.0	1.0	1.0	1.0	0 (0, 0)	0 (0, 0)
10–14	0.910 (0.140)	1.0	1.0	1.0	1.0	0 (0, 0)	0 (0, 0)
15–19	0.896 (0.154)	1.0	1.0	1.0	1.0	9.5 (7.8, 11.1)	8.9 (7.3, 10.5)
20–24	0.905 (0.158)	1.0	1.0	1.0	1.0	31.4 (29.3, 33.5)	22.9 (21.0, 24.8)
25–29	0.909 (0.159)	1.0	1.0	1.0	1.0	31.4 (29.3, 33.5)	22.9 (21.0, 24.8)
30–34	0.909 (0.160)	1.0	1.0	1.0	1.0	31.4 (29.3, 33.5)	22.9 (21.0, 24.8)
35–39	0.907 (0.164)	3.0	1.1	1.0	1.0	27.7 (25.1, 30.3)	18.4 (16.4, 20.4)
40–44	0.883 (0.195)	3.2	1.0	1.0	1.0	27.7 (25.1, 30.3)	18.4 (16.4, 20.4)
45–49	0.862 (0.209)	2.8	2.1	7.0	22.1	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
50–54	0.846 (0.221)	3.1	1.9	21.1	11.3	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
55–59	0.841 (0.219)	3.0	2.2	39.0	16.6	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
60–64	0.846 (0.213)	2.7	2.3	31.3	14.3	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
65–69	0.846 (0.210)	2.6	2.3	27.0	17.1	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
70–74	0.825 (0.221)	2.5	2.1	26.0	10.2	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
75–79	0.796 (0.243)	2.1	1.9	21.5	12.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
80–84	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
85–89	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
90–94	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
95–99	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)

death (Eq. 2) and can therefore incorporate a change in radon exposure rate during the time since exposure modeled:

$$\eta_t = \Delta_{[5,14]}(t) + \theta_2 \Delta_{[15,24]}(t) + \theta_3 \Delta_{[25+]}(t) \quad (2)$$

And $\Delta_{[a,b]}(t) = \{10 \text{ for } t > b; (t - a) \text{ for } a \leq t \leq b; 0 \text{ otherwise}\}$

Central estimates of the parameter values for the modifying factors (derived from an overall fit of the BEIR VI EAC model to 11 miner cohort studies taken from Krewski et al. (1999)) were described in greater detail in Brand et al. (2005).

Quality of life

Health-related quality of life is characterized using the age-specific values (Table 2) for Health Utilities Index Mark 3 (HUI3), a standardized instrument used as a measure of eight dimensions of health-related quality of life, reported in the CCHS for 2009–2010 (Statistics Canada 2010). The change in quality of life is assessed only in terms of mortality (the disutility due to lung cancer morbidity is not included) and will likely lead to results that are conservative.

Analysis

The base analysis models the lung cancer risk associated with current radon exposures. Two interventions to prevent radon entry into new construction were applied to the housing stock exposed to residential radon, and the number of lung cancer deaths prevented and the associated QALYs gained are calculated by comparing each scenario to the base model. The two interventions investigated are preventive radon measures installed at construction, resulting in a 50% reduction in radon, and an active depressurization system, resulting in an 85% reduction in radon. The percentage of housing that is exposed to residential radon for each target population listed in Table 1 was estimated from the 2011 National Household Survey (Statistics Canada 2011b).

Uncertainty

A Monte Carlo simulation with 10,000 samples from the distributions for radon exposure, age-specific health utilities, lung cancer mortality rates, and smoking prevalence by age group and sex was conducted to assess the uncertainty. The mean and 95% credible interval (2.5% and 97.5% quantiles of the simulated results) were estimated for the number of lung cancer deaths prevented and associated gain in QALYs for the 2012 Canadian population, each provincial population, and those of 17 CMAs.

Results

The annual radon-attributed lung cancer deaths prevented and associated period QALYs gained and QALYs per 100,000 people gained in Canada for proposed intervention 1 and intervention 2 are listed in Table 3. The results are non-linear with respect to radon reduction for both attributed lung cancer deaths prevented and QALYs gained, with the benefit from an 85% reduction nearly double that from a 50% reduction. The total QALY gain using a discount rate of 1.5% for the Canadian population for intervention 1, a 50% reduction in residential radon, is 15,445 (95% CI 1180–51,691), and for intervention 2, an 85% reduction in radon, is 26,336 (95% CI 2006–88,339). For a discount rate of zero, the QALY gains are higher, at 39,253 (95% CI 2999–131,346) for intervention 1 and 66,953 (95% CI 5098–224,619) for intervention 2. The QALY gain for women in Canada is higher than for men across all categories; for example, the QALY gain at a discount rate of 1.5% for intervention 2 was 14,863 (95% CI 1134–49,853) for women and 11,473 (95% CI 872–38,457) for men. The QALY gain for intervention 2 at a discount rate of 1.5% is 85 per 100,000 women (95% CI 6–285) and 67 per 100,000 men (95% CI 5–223). The QALY gain per 100,000 smokers is higher than per 100,000 non-smokers for both men and women because radon-attributable lung cancer mortality is more common among smokers. Similarly, the total QALY gain for smokers in the Canadian population is also higher than for non-smokers, for both men and women, despite the far greater number of non-smokers than smokers in the population. The QALY gain for intervention 2 at a discount rate of 1.5% for male non-smokers in the Canadian population is 3521 (95% CI 262–111,914) and 7952 (95% CI 606–26,442) for male smokers, and for female non-smokers is 8382 (95% CI 647–27,881) and 6480 (95% CI 490–21,877) for female smokers.

The annual number of preventable radon-attributable lung cancer deaths for Canada (Table 3) is 681 (95% CI 100–1284) for intervention 1 and 1263 (95% CI 171–2571) for intervention 2. The number of preventable radon-attributable lung cancer deaths is higher for men than for women, and higher for smokers than non-smokers for both men and women, because most radon-attributable lung cancer deaths occur in smokers and smoking prevalence is higher among men than women.

The annual radon-attributed lung cancer deaths prevented and associated period QALYs gained and QALYs per 100,000 people gained in the Canadian provinces and territories for proposed intervention 1 and intervention 2 are listed in Table 4. The total QALY gains are highest for provinces with the largest populations, ranging for intervention 2 at a discount rate of 1.5% from 7045 (95% CI 450–24,771) for Quebec and 6529 (95% CI 519–24,168) for Ontario to 55 (95% CI 3–202)

Table 3 Canada: period QALYs, QALYs per 100,000 people, and annual radon-attributed lung cancer deaths prevented

Canada	Total	Male	Female	Male non-smoker	Male smoker	Female non-smoker	Female smoker
QALYs (DR = 0)							
Intervention 1, mean (95% CI)	39,253 (2999–131,346)	17,012 (1297–56,891)	22,241 (1702–74,438)	5264 (391–17,803)	11,748 (900–38,947)	9754 (738–32,906)	12,487 (968–41,384)
Intervention 2, mean (95% CI)	66,953 (5098–224,619)	29,021 (2206–97,323)	37,932 (2893–127,267)	8953 (665–30,289)	20,069 (1530–66,779)	16,595 (1254–56,022)	21,336 (1646–70,981)
QALYs (DR = 1.5%)							
Intervention 1, mean (95% CI)	15,445 (1180–51,691)	6728 (513–22,495)	8717 (667–29,179)	2071 (154–7003)	4657 (357–15,437)	3809 (288–12,852)	4908 (381–16,268)
Intervention 2, mean (95% CI)	26,336 (2006–88,339)	11,473 (872–38,457)	14,863 (1134–49,853)	3521 (262–11,914)	7952 (606–26,444)	6480 (490–21,877)	8382 (647–27,881)
QALYs per 100,000 people (DR = 0)							
Intervention 1, mean (95% CI)	113 (9–378)	99 (8–330)	127 (10–425)	41 (3–137)	276 (21–914)	68 (5–231)	386 (30–1280)
Intervention 2, mean (95% CI)	193 (15–646)	168 (13–565)	217 (17–726)	69 (5–234)	472 (36–1568)	117 (9–393)	659 (51–2196)
QALYs per 100,000 people (DR = 1.5%)							
Intervention 1, mean (95% CI)	45 (3–149)	39 (3–131)	50 (4–167)	16 (1–54)	109 (8–363)	27 (2–90)	152 (12–503)
Intervention 2, mean (95% CI)	76 (6–254)	67 (5–223)	85 (6–285)	27 (2–92)	187 (14–621)	45 (3–153)	259 (20–862)
Radon-attributable lung cancer deaths prevented							
Intervention 1, mean (95% CI)	681 (100–1284)	357 (50–691)	324 (49–593)	56 (10–91)	301 (40–601)	102 (19–162)	222 (31–433)
Intervention 2, mean (95% CI)	1263 (171–2571)	660 (86–1378)	603 (85–1195)	107 (18–185)	553 (69–1,911)	194 (33–331)	409 (52–864)

Table 4 Provinces and CMAs: period QALYs, QALYs per 100,000 people, and annual radon-attributed lung cancer deaths prevented

Province	QALYs (DR = 0)		QALYs (DR = 1.5%)		QALYs per 100,000 people (DR = 0)		QALYs per 100,000 people (DR = 1.5%)		Lung cancer deaths prevented	
	Interv. 1	Interv. 2	Interv. 1	Interv. 2	Interv. 1	Interv. 2	Interv. 1	Interv. 2	Interv. 1	Interv. 2
NL	735 (47–2727)	1253 (79–4663)	291 (18–1079)	495 (31–1844)	140 (9–518)	238 (15–886)	55 (3–205)	94 (6–350)	15 (2–31)	27 (3–62)
St. John's	308 (33–857)	525 (55–1462)	122 (13–339)	208 (22–578)	156 (17–435)	266 (28–742)	62 (7–172)	105 (11–294)	5 (1–8)	10 (2–17)
NS	1461 (72–5081)	2492 (122–8684)	577 (28–2004)	983 (48–3424)	155 (8–538)	264 (13–919)	61 (3–212)	104 (5–362)	26 (3–51)	48 (5–103)
Halifax	791 (54–2494)	1352 (92–4276)	313 (21–987)	535 (36–1691)	203 (14–639)	346 (23–1095)	80 (5–253)	137 (9–433)	11 (2–16)	22 (3–33)
PEI	147 (10–660)	251 (16–1126)	58 (4–259)	99 (6–442)	102 (7–455)	173 (11–776)	40 (3–178)	68 (4–305)	3 (0–7)	5 (1–13)
NB	1667 (84–5995)	2849 (143–10,304)	658 (33–2364)	1124 (56–4059)	220 (11–792)	377 (19–1362)	87 (4–312)	148 (7–536)	26 (3–43)	49 (5–87)
St. John	231 (19–647)	394 (33–1108)	91 (8–256)	155 (13–438)	180 (15–507)	308 (26–867)	71 (6–200)	122 (10–343)	4 (1–6)	7 (1–12)
QC	10,462 (671–36,690)	17,857 (1141–62,779)	4129 (265–14,485)	7045 (450–24,771)	129 (8–454)	221 (14–777)	51 (3–179)	87 (6–306)	183 (23–356)	341 (40–720)
Quebec	1481 (126–4050)	2530 (214–6938)	584 (50–1599)	998 (85–2737)	193 (16–529)	330 (28–906)	76 (6–209)	130 (11–357)	22 (4–33)	42 (7–68)
Sherbrooke	583 (66–1814)	997 (113–3123)	230 (26–715)	393 (45–1229)	289 (33–898)	494 (56–1547)	114 (13–354)	195 (22–609)	7 (2–9)	14 (4–19)
Montreal	6109 (551–15,745)	10,433 (937–26,959)	2410 (218–6213)	4115 (370–10,631)	160 (14–412)	273 (25–705)	63 (6–162)	108 (10–278)	93 (19–139)	177 (32–284)
ON	9715 (774–35,905)	16,560 (1316–61,322)	3831 (305–14,157)	6529 (519–24,168)	72 (6–268)	123 (10–457)	29 (2–106)	49 (4–180)	195 (29–399)	360 (50–797)
Ottawa-Gatineau (NCR)	1427 (179–3351)	2433 (305–5727)	564 (71–1325)	962 (121–2263)	115 (14–271)	197 (25–463)	46 (6–107)	78 (10–183)	24 (6–35)	46 (11–70)
Kingston	315 (48–694)	537 (81–1188)	124 (19–273)	212 (32–467)	197 (30–435)	337 (51–745)	78 (12–171)	133 (20–293)	4 (2–5)	8 (3–11)
Toronto	3327 (440–10,264)	5669 (748–17,519)	1314 (174–4052)	2238 (295–6914)	60 (8–184)	102 (13–314)	24 (3–73)	40 (5–124)	71 (16–125)	131 (28–248)
Windsor	625 (118–1144)	1067 (200–1956)	246 (46–451)	420 (79–770)	196 (37–358)	334 (63–613)	77 (15–141)	132 (25–241)	9 (4–11)	17 (6–22)
MB	2243 (260–5607)	3827 (442–9587)	884 (103–2210)	1508 (174–3777)	179 (21–449)	306 (35–767)	71 (8–177)	121 (14–302)	33 (9–45)	63 (15–91)
Winnipeg	2987 (583–7773)	5101 (992–13,333)	1177 (230–3065)	2010 (391–5253)	239 (47–622)	408 (79–1067)	94 (18–245)	161 (31–420)	36 (17–43)	71 (30–87)
SK	1852 (236–4440)	3159 (402–7588)	730 (93–1752)	1245 (159–2993)	171 (22–409)	291 (37–699)	67 (9–161)	115 (15–276)	29 (8–41)	55 (14–83)
Saskatoon	493 (110–862)	841 (187–1474)	195 (43–340)	332 (74–582)	189 (42–331)	323 (72–565)	75 (17–131)	128 (28–223)	7 (3–8)	13 (6–17)
Regina	593 (76–1798)	1015 (130–3095)	234 (30–710)	401 (51–1221)	282 (36–854)	482 (62–1470)	111 (14–337)	190 (24–580)	6 (2–7)	12 (4–15)
AB	3201 (418–8410)	5454 (711–14,359)	1269 (166–3331)	2161 (282–5682)	83 (11–217)	141 (18–370)	33 (4–86)	56 (7–146)	68 (17–106)	128 (29–211)
Edmonton	1312 (230–2706)	2236 (392–4619)	519 (91–1071)	885 (155–1827)	113 (20–233)	193 (34–398)	45 (8–92)	76 (13–158)	24 (9–32)	46 (15–65)
Calgary	1313 (237–2567)	2238 (402–4382)	521 (94–1019)	888 (160–1738)	108 (19–211)	184 (33–361)	43 (8–84)	73 (13–143)	24 (9–30)	45 (16–61)
BC	2574 (286–10,307)	4383 (487–17,584)	1014 (113–4060)	1726 (192–6926)	57 (6–227)	96 (11–387)	22 (2–89)	38 (4–152)	58 (10–132)	105 (17–258)
Kelowna	396 (57–848)	676 (97–1451)	155 (22–333)	265 (38–569)	220 (32–472)	376 (54–807)	86 (12–185)	148 (21–317)	5 (2–7)	10 (3–15)
Vancouver	895 (101–3744)	1523 (171–6384)	353 (40–1477)	601 (67–2517)	39 (4–162)	66 (7–276)	15 (2–64)	26 (3–109)	22 (4–54)	39 (6–105)
NU	14 (3–43)	24 (5–73)	6 (1–17)	10 (2–30)	41 (8–123)	70 (14–210)	17 (3–50)	28 (6–85)	0 (0–1)	1 (0–2)
NT	78 (5–294)	133 (8–501)	31 (2–118)	54 (3–202)	179 (10–674)	305 (18–1150)	72 (4–271)	123 (7–463)	1 (0–2)	1 (0–3)
YT	372 (28–1132)	637 (48–1954)	148 (11–450)	253 (19–776)	1031 (78–3140)	1768 (132–5420)	410 (31–1248)	702 (52–2152)	2 (1–4)	5 (1–8)

for the Northwest Territories and 10 (95% CI 2–30) for Nunavut. The QALY gains per 100,000 population are highest for the areas of highest radon in Canada: at 148 (95% CI 7–536) for New Brunswick, 121 (95% CI 14–302) for Manitoba, 115 (95% CI 15–276) for Saskatchewan, and substantially greater in the Yukon, at 702 (95% CI 52–2152) for intervention 2 at a discount rate of 1.5%. The lowest values are 28 per 100,000 people (95% CI 6–85) for Nunavut and 38 per 100,000 people (95% CI 4–152) for BC. The absolute number of preventable radon-attributed lung cancer deaths were also highest for provinces with higher populations, ranging for intervention 2 from 341 (95% CI 40–720) for Quebec to 360 (95% CI 50–797) for Ontario to 1 (95% CI 0–2) for Nunavut and 1 (95% CI 0–3) for the Northwest Territories.

The individual period QALY gains in Canada for the reduction in radon from the geometric mean achieved by intervention 2, by age category for male smokers, male non-smokers, female smokers, and female non-smokers at discount rate of 0, are plotted in Fig. 1. The QALY gains all follow the same trend: zero until about age 50, peaking at age group 75–79 years, and falling nearly to zero at about age 95. The QALY gains begin to increase after about age 50 because they are associated with the prevention of radon-attributed lung cancer death, and lung cancer mortality rates are very low before age 50. The individual annual QALY gains are higher for smokers than non-smokers, and higher for females than males.

The annual radon-attributed lung cancer deaths prevented and associated period QALYs gained and QALYs per 100,000 people gained in 17 census metropolitan areas in Canada for

proposed intervention 1 and intervention 2 are listed in Table 4. The total QALY gains and number of preventable radon-attributable lung cancer deaths are highest for the CMAs with the highest populations. The total QALY gains for intervention 2 at a discount rate of 1.5% range from 4115 (95% CI 370–10,631) for Montreal, QC, and 2238 (95% CI 295–6914) for Toronto, ON, to a low of 155 (95% CI 13–438) for St. John, NB. The number of preventable radon-attributable lung cancer deaths for intervention 2 ranges from 177 (95% CI 32–284) for Montreal, QC, and 131 (95% CI: 28–248) for Toronto, ON, to 7 (95% CI 1–12) for St. John, NB. The QALY gains per 100,000 people are highest for CMAs with the highest radon exposures: at 195 (95% CI 22–609) for Sherbrooke, 190 (95% CI 24–580) for Regina, 161 (95% CI 31–420) for Winnipeg, and 148 (95% CI 21–317) for Kelowna (low smoking prevalence and high percentage of housing exposed to radon) for intervention 2 at a discount rate of 1.5%. The lowest QALY gains per 100,000 people for intervention 2 at a discount rate of 1.5% are 26 (95% CI 3–109) for Vancouver and 40 (95% CI 5–124) for Toronto, cities characterized by low residential radon and a lower percentage of housing exposed to radon.

Discussion

Residential radon is an important and modifiable cause of lung cancer in Canada. Smoking is the most important modifiable cause of lung cancer, and although one third of smokers in Canada express an intention to quit smoking within a month,

Fig. 1 Individual period QALY gains in Canada for the reduction in radon from the geometric mean achieved by intervention 2 by age, sex, and smoking status, at discount rate of 0

long-term success is elusive even when it is defined as quitting for 6 or 12 months (CADTH 2011). Radon mitigation is the most important intervention to reduce lung cancer among non-smokers, and reducing indoor radon benefits all current and future residents of the structure mitigated, regardless of smoking status, over the lifetime of the structure (Conrath and Pawel 2013). The estimates for period QALY gain from reducing the residential radon levels in Canada by 50% is 15,445 (95% CI 1180–51,691) and by 85% is 26,336 (95% CI 2006–88,339), discounted at 1.5% [undiscounted 39,253 (95% CI 2999–131,346) and 66,953 (95% CI 5098–224,619)], and the annual number of preventable radon-attributed lung cancer deaths is 681 (95% CI 100–1284) and 1263 (95% CI 171–2571), respectively. The highest QALYs and number of preventable radon-attributed lung cancer deaths among the provinces/territories and CMAs are for those with the highest radon exposures and largest populations. This analysis demonstrates the potential benefits to Canadians from improved life expectancy and quality of life from reducing the radon-attributable burden of lung cancer mortality in new housing.

The number of radon-attributable lung cancer deaths that might be prevented by theoretical reductions in residential radon were estimated for Canada (Al-arydah 2018; Chen et al. 2012). Remediation of houses with radon above 800 (200, 100) Bq/m³ would result in 90 (927, 1704) deaths averted annually out of a total of 3261 lung cancer deaths attributed to residential radon in Canada (Chen et al. 2012). The concave shape of plots of increasing PAR with increasing action/threshold for radon remediation in existing housing, in all five Canadian provinces assessed, similarly demonstrates that greater relative benefit would be derived for lower action/threshold levels for radon mitigation (Al-arydah 2018). The passive preventive measures and active depressurization systems evaluated in this analysis for new construction reduce the smaller risks experienced by the middle of the distribution and prevent a far greater number of cases of a disease than adopting a strategy preventing only the highest risk, described by Rose (2008) as a “targeted rescue operation for vulnerable individuals” at the tail of the distribution.

The period QALY gains per 100,000 people identify the provinces/territories and CMAs where radon reduction would have the greatest benefit, independent of population size: the Yukon, New Brunswick, Manitoba, and Saskatchewan; and Sherbrooke, Regina, Winnipeg, Kelowna, and Halifax. The much higher values of QALY gains per 100,000 people for both interventions in the Yukon is the result of the much higher cancer mortality rates recently reported for the Yukon compared to national, provincial, urban, and southern-rural jurisdictions (Simkin et al. 2017). Comparison of the Yukon and Canadian 5-year cumulative rolling lung cancer age-standardized mortality rates (ASMRs) by sex demonstrate much higher rates for the Yukon than the Canadian average for both men and women, and that while this difference has

decreased for men, it has increased for women over the years 1999–2013. The Yukon is a high radon area in Canada, and a greater benefit would be derived from preventing some of this much larger lung cancer burden. Factors that contribute to this burden include higher smoking rates, and physical and cultural barriers to health promotion and care services and end-of-life care.

A global analysis recently quantified the increased mortality and lung cancer from environmental exposure to particulate air pollution (Evans et al. 2013) and the gain in quality-adjusted life expectancy associated with a uniform reduction in sulfate air pollution in Canada was estimated to be 20,960 QALYs discounted at 5% and 25,520 QALYs undiscounted (Coyle et al. 2003). For Canada, the undiscounted period QALY gain for a 50% (85%) reduction in residential radon was about 1.5 (2.5) times the undiscounted annual QALY gain from a 1 µg/m³ reduction in sulfate air pollution.

The most significant limitation of this analysis is that it estimates the burden of disease that could be removed by practical interventions in new construction, yielding estimates of the maximum potential benefit from theoretical radon mitigation of all housing stock in 2012. Another limitation is that the percentage of radon reduction for both passive preventive measures and active depressurization systems is assumed to be independent of the initial radon level (though the absolute reduction is lower), due to insufficient data describing the rate and threshold at which the reduction would decrease. It was assumed that the relative risks of all-cause and lung cancer mortality between smokers and non-smokers derived from the US were applicable to Canada due to the similarity of the two populations.

Assessment of practical policies in Canada would require a comprehensive health economic evaluation of interventions to reduce residential radon in new and existing housing in Canada. Evaluation of the maximum potential benefit that could be derived from practical and effective radon interventions is important so that new radon remediation strategies can be identified and evaluated instead of limiting a future cost-effectiveness analysis to evaluation of current radon remediation approaches. The results of this analysis suggest that active soil depressurization might be cost-effective in new construction for populations in Canada exposed to higher residential radon. The increasing proportion of the total housing stock with radon mitigation measures over time following a policy change will require modeling the rate of uptake and costs of radon mitigation retrofits for existing buildings and annual housing starts occurring after building code changes regulating radon prevention in new construction. Ongoing updating of the national radon survey by the National Radon Program, probably every 20 years or so, will measure the effect of building code changes and education and incentives to encourage mitigation of existing housing on residential radon exposures.

Conclusions

Radon is a modifiable environmental exposure in Canada that is currently the second most important cause of lung cancer after smoking. In Canada, lung cancer is the most common cause of cancer mortality for both men and women. Gains in quality-adjusted life expectancy from potential reductions in the modifiable lung cancer burden attributable to residential radon were assessed at the national, provincial, and municipal levels, all of which are involved in regulating indoor air quality. A reduction in residential radon by 50% could prevent 681 annual radon-attributable lung cancer deaths, associated with a period gain of 15,445 QALYs, and a reduction by 85% could prevent 1263 annual radon-attributable lung cancer deaths, associated with a period gain of 26,336 QALYs, for the Canadian population at a discount rate of 1.5%. Regional analyses indicate that provincial/territorial populations that would derive the greatest quality-adjusted life expectancy from radon reduction include those in the Yukon, New Brunswick, Manitoba, and Saskatchewan, and the municipal populations of Sherbrooke, Regina, Winnipeg, Kelowna, and Halifax.

References

- Al-arydah, M. (2017). Population attributable risk associated with lung cancer induced by residential radon in Canada: Sensitivity to relative risk model and radon probability density function choices: In memory of Professor Jan M. Zielinski. *Sci Total Environ*, 596–597, 331–341. <https://doi.org/10.1016/j.scitotenv.2017.04.067>.
- Al-arydah, M. (2018). Estimating the burden of lung cancer and the efficiency of home radon mitigation systems in some Canadian provinces. *Sci Total Environ*, 626, 287–306. <https://doi.org/10.1016/j.scitotenv.2018.01.028>.
- Andersen, C. E., Bergsøe, N. C., Brendstrup, J., Damkjær, A., Gravesen, P., & Ulbak, K. (1997). *Radon-95 : En undersøgelse af metoder til reduktion af radonkoncentrationen i danske enfamiliehuse*. Technical University of Denmark, Denmark. Forskningscenter Risøe. Risøe-R; Nr. 979(DA).
- Angell, W. (2013). Radon control in new homes: A meta-analysis of 25 years of research. *Am Assoc Radon Sci Technol* 45.
- Brand, K. P., Zielinski, J. M., & Krewski, D. (2005). Residential radon in Canada: An uncertainty analysis of population and individual lung cancer risk. *Risk Anal*, 25, 253–269. <https://doi.org/10.1111/j.1539-6924.2005.00587.x>.
- Canadian Agency for Drugs and Technologies in Health (CADTH) (2011). CADTH Smoking Cessation Scientific Summary. Available: https://www.cadth.ca/media/pdf/CADTH_Smoking_Cessation_Scientific_Summary_e.pdf.
- Canadian Agency for Drugs and Technologies in Health (CADTH) (2017). Guidelines for the Economic Evaluation of Health Technologies: Canada (4th Edition). Available: https://www.cadth.ca/sites/default/files/pdf/guidelines_for_the_economic_evaluation_of_health_technologies_canada_4th_ed.pdf.
- Canadian Cancer Society, Statistics Canada, Public Health Agency of Canada, Provincial/Territorial Cancer Registries (2014). Canadian Cancer Statistics 2014. Can Cancer Stat. Available: http://www.cancer.ca/~media/cancer.ca/CW/cancerinformation/cancer_101/Canadian_cancer_statistics/Canadian-Cancer-Statistics-2014%2D%2DEN.pdf.
- Chen, J., Moir, D., & Whyte, J. (2012). Canadian population risk of radon induced lung cancer: A re-assessment based on the recent cross-Canada radon survey. *Radiat Prot Dosim*, 152, 9–13. <https://doi.org/10.1093/rpd/ncs147>.
- Chen, J., Bergman, L., Falcomer, R., & Whyte, J. (2014). Results of simultaneous radon and Thoron measurements in 33 metropolitan areas of Canada. *Radiat Prot Dosim*, 163, 1–7. <https://doi.org/10.1093/rpd/ncu141>.
- Conrath, S., & Pawel, D. (2013). Letter to the Editor: Lung cancer efforts need stronger emphasis on reducing radon. *Am J Public Health*, 103, e4. <https://doi.org/10.2105/AJPH.2013.301436>.
- Coyle, D., Stieb, D., Burnett, R., Decivita, P., Krewski, D., Chen, Y., et al. (2003). Impact of particulate air pollution on quality-adjusted life expectancy in Canada. *J Toxicol Environ Health A*, 66, 1847–1863. <https://doi.org/10.1080/152873903006447>.
- Dunn, B., & Cooper, K. (2014). *Radon in indoor air: a review of policy and law in Canada*. Toronto: Canadian Environmental Law Association. CELA Publication # 1008.
- Evans, J., van Donkelaar, A., Martin, R. V., Burnett, R., Rainham, D. G., Birkett, N. J., et al. (2013). Estimates of global mortality attributable to particulate air pollution using satellite imagery. *Environ Res*, 120, 33–42. <https://doi.org/10.1016/j.envres.2012.08.005>.
- Gray, A., Read, S., McGale, P., & Darby, S. (2009). Lung cancer deaths from indoor radon and the cost effectiveness and potential of policies to reduce them. *BMJ*, 338, a3110. <https://doi.org/10.1136/bmj.a3110>.
- Health Canada (2012). Cross-Canada survey of radon concentrations in homes—Final report. Available: <http://www.hc-sc.gc.ca/ewh-semt/radiation/radon/survey-sondage-eng.php>.
- Health Canada (2016). Summary report on active soil depressurization (ASD) field study. Available: <https://www.canada.ca/en/health-canada/services/environmental-workplace-health/radiation/radon/summary-report-active-soil-depressurization-field-study.html>.
- Howlader N, Noone A, Krapcho M, Neyman N, Aminou R, Waldron W, et al. (2012). SEER Cancer statistics review 1975–2009.
- IHME (2013). GBD PROFILE : CANADA 2010. Available: http://www.healthdata.org/sites/default/files/files/country_profiles/GBD/ihme_gbd_country_report_canada.pdf.
- Jaswal A. (2013). Valuing health in Canada: Who, how, and how much? Canada 2020 Analytical Commentary. Available: <http://canada2020.ca/wp-content/uploads/2013/06/Canada-2020-Analytical-Commentary-No-3-Valuing-Health-in-Canada-FINAL.pdf>.
- Kenfield, S. A., Stampfer, M. J., Rosner, B. A., & Colditz, G. A. (2008). Smoking and smoking cessation in relation to mortality in women. *JAMA*, 299, 2037–2047. <https://doi.org/10.1001/jama.299.17.2037>.
- Krewski, D., Rai, S. N., Zielinski, J. M., & Hopke, P. K. (1999). Characterization of uncertainty and variability in residential radon cancer risks. *Annals of the New York Academy of Sciences*, 895, 245–272.
- National Research Council (1999). *Health effects of exposure to radon: BEIR VI*. Washington, DC: National Academies Press.
- Pesch, B., Kendzia, B., Gustavsson, P., Jöckel, K., Johnen, G., Pohlabein, H., et al. (2012). Cigarette smoking and lung cancer—Relative risk estimates for the major histological types from a pooled analysis of case-control studies. *Int J Cancer*, 131, 1210–1219. <https://doi.org/10.1002/ijc.27339>.
- Peterson, E., Aker, A., Kim, J., Li, Y., Brand, K., & Copes, R. (2013). Lung cancer risk from radon in Ontario, Canada: How many lung cancers can we prevent? *Cancer Causes Control*, 24, 2013–2020. <https://doi.org/10.1007/s10552-013-0278-x>.
- Rose, G. (2008). The population strategy of prevention. In *Rose's strategy of preventive medicine* (p. 192). New York: Oxford University Press.
- Simkin, J., Woods, R., & Elliott, C. (2017). Cancer mortality in Yukon 1999–2013: Elevated mortality rates and a unique cancer profile.

- International Journal of Circumpolar Health*, 76, 9. <https://doi.org/10.1080/22423982.2017.1324231>.
- Statistics Canada (2010). Canadian Community Health Survey (CCHS) 2009–2010: derived variables. 199 pages. Available: http://www23.statcan.gc.ca/imdb-bmdi/pub/document/3226_D71_T9_V1-eng.pdf. Accessed 10 Aug 2017.
- Statistics Canada (2011a). Estimates of population by census metropolitan area, sex and age group for July 1, based on the Standard Geographical Classification (SGC) 2011. Table 051–0056. Available: <http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=0510056&pattern=&stByVal=1&p1=1&p2=37&tabMode=dataTable&csid=>.
- Statistics Canada (2011b). National Household Survey: Structural type of dwelling. Available: <http://www12.statcan.gc.ca/nhs-enm/2011/dp-pd/dt-td/0p-eng.cfm?LANG=E&APATH=3&DETAIL=0&DIM=0&FL=A&FREE=0&GC=0&GID=0&GK=0&GRP=0&PID=106699&PRID=0&PTYPE=105277&S=0&SHOWALL=0&SUB=0&Temporal=2013&THEME=98&VID=0&VNAMEE=&VNAMEF=>.
- Statistics Canada (2012a). Deaths and mortality rates, by age group and sex, Canada, provinces and territories. Table 102–0504. Available: <http://www5.statcan.gc.ca/cansim/a26?lang=eng&id=1020504>.
- Statistics Canada (2012b). Estimates of population, by age group and sex for July 1, Canada, provinces and territories. Table 051–0001. Available: <http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=0510001&pattern=&stByVal=1&p1=1&p2=37&tabMode=dataTable&csid=> [accessed 10 August 2017].
- Statistics Canada (2012c). New cases of primary cancer (based on the July 2016 CCR tabulation file), by cancer type, age group and sex, Canada, provinces and territories. Table 103–0550. Available: <http://www5.statcan.gc.ca/cansim/a26?lang=eng&id=1030550>.
- Statistics Canada (2013). Health indicator profile, two year period estimates, by age group and sex, Canada, provinces, territories, health regions (2013 boundaries) and peer groups. Table 105–0502. Available: <http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=1050502&pattern=&csid=>.
- Thun, M. J., Myers, D. G., Day-Lally, C., Namboodiri, M. M., Calle, E. E., Flanders, W. D., et al. (1997). *Age and the exposure–response relationships between cigarette smoking and premature death in Cancer Prevention Study II*. Smoking and Tobacco Control Monograph No. 8. NIH Publication No. 97-4213. Bethesda: National Institutes of Health.
- Villeneuve, P., & Mao, Y. (1994). Lifetime probability of developing lung cancer, by smoking status, Canada. *Canadian Journal of Public Health*, 85, 385–388.
- Wooliscroft, M., Scivyer, C., & Parkins, L. (1994). Field trials on the effectiveness of radon protection measures in new dwellings. *Radiation Protection Dosimetry*, 56, 33–40.