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Indoor radon trends with building code change in two Canadian cities

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ABSTRACT

Radon studies were conducted in two Canadian cities, in Halifax, Nova Scotia, and Winnipeg, Manitoba, to evaluate trends in indoor radon before and after the 2010 National Building Code of Canada was adopted into the legally binding provincial building codes in 2011. Participants were recruited in neighbourhoods characterized by newer housing developments. A postcard campaign in each city offered free radon testing to every house in the target areas, and free testing kits were mailed to study participants. Indoor radon measurements and house questionnaires were completed by 225 eligible participants in Halifax and 171 eligible participants in Winnipeg, using alpha-track radon detectors deployed for three months during the heating season in 2021–2022. Multivariate logistic regression analyses were conducted to evaluate the association between indoor radon and the period of construction, the area in contact with the ground, the number of storeys, the type of heating system, the water source, and the type of ventilation. These analyses were focussed on the detached study houses because the majority of the participants lived in a detached house, and significant associations were identified for the period of construction and the floor where the radon detector was located. An odds ratio of 1.91 (1.04–3.50) for the detached Halifax study houses built after 2011 was associated with having a higher than geometric mean radon concentration ($p = 0.033$), nearly double the likelihood. There was no evidence of significant change in the indoor radon after 2011 in the detached Winnipeg study houses. A lower likelihood – almost half - for measurement conducted on a main/upper floor compared to in the basement was associated with a radon concentration above the respective geometric mean for each city: an odds ratio of 0.48 (0.27–0.86) for the detached Halifax study houses ($p = 0.012$), and of 0.45 (0.32–0.64) for the detached Winnipeg study houses ($p = 0.022$). Radon is the second most important cause of lung cancer, after smoking, and the results of this study support strengthening the radon preventive measures required in new low-rise housing to reduce the associated lung cancer burden in Canada.

1. Introduction

Radon is a naturally occurring radioactive gas that causes lung cancer in humans (IARC, 1988). In Canada, radon is reported to be the most important cause of lung cancer for non-smokers, and the second leading cause of lung cancer for smokers (Health Canada, 2023). Released during the radioactive decay of uranium in the rock and soil, radon gas can infiltrate into buildings through cracks and joints in foundation floors and walls and accumulate indoors. The World Health Organization recommends that countries develop a national strategy to reduce both the population exposure to radon by implementing measures in building codes to reduce radon ingress in new construction, and to reduce the risk for those exposed to high concentrations by establishing a national reference level to guide testing and mitigation once the buildings are occupied (WHO, 2009).

Residential radon exposures have decreased in several European countries following building code changes mandating new or increased radon preventive measures for low-rise housing. The installation of a radon/damp-proof membrane, of at least 300 μm thick polyethylene, has been required in new housing since 1999 in designated radon affected areas in England, and since 1998 in Ireland (Dowdall et al., 2017; Hodgson et al., 2019). A 42% decrease in geometric mean radon was reported for high radon areas in England following the change in building code (Hodgson et al., 2019), and a 45% decrease in the arithmetic mean radon concentration was reported in high radon areas in Northamptonshire (Denman et al., 2018). In Ireland, it was reported that the arithmetic mean radon concentration had decreased by 26% in houses built after the 1998 building code change (Dowdall et al., 2017). Residential radon reductions were reported in two Nordic countries following changes to the building code that included a passive vertical depressurization stack and sealing measures in the foundation for house types at higher risk of radon infiltration. In Norway, it was reported that the arithmetic mean radon concentration was reduced by 47% in detached houses and by 34% in semi-detached and terraced houses after the building code was changed in 2010 to require a sub-slab radon membrane and a passive vertical depressurization stack in new houses

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(Finne et al., 2019; Haanes et al., 2022). Similarly, in Finland, a reduction of 47% in the arithmetic mean radon concentration was attributed to the installation of foundation sealing strips and a passive vertical stack in 83% of low-rise housing in high radon areas in Finland, following changes made to the building code and associated practical guidelines in 2004 (Arvela et al., 2012).

The health burden from residential radon exposure is substantial in Canada: roughly 3000 radon-attributable lung cancer cases are estimated to occur annually (Chen et al., 2012; Gaskin et al., 2020). Since 2007, Health Canada has recommended that radon ingress be minimized in new construction and that existing buildings be tested for radon, and that remedial measures be undertaken in existing buildings should a radon concentration above the guideline value of 200 Bq/m^3 be measured in the normal occupancy area (Health Canada, 2017). Radon control measures were introduced into the National Building Code (NBC) of Canada for low-rise housing in 2010 (Canadian Commission on Building and Fire Codes, 2022). The primary change was the requirement to install a pipe stub through the concrete slab into a sub-slab gravel layer so that a future radon depressurization system could be activated after construction is completed. New sealing requirements were prescribed so the foundation barrier of minimum thickness 6 mil (150 μm) polyethylene already required as a vapour barrier would also provide an airtight radon and soil gas barrier.

The radon preventive measures introduced and highlighted in the 2010 NBC model code were adopted into the legally binding provincial building code of Manitoba, implemented in April 2011, and of Nova Scotia, implemented in June 2011, and subsequently in many other provinces (National Research Council of Canada, 2020). To assess their effectiveness, residential radon surveys were conducted during the 2021–2022 heating season in houses built during the decades before and after 2011, in the capital city of Manitoba and of Nova Scotia. Residents were also asked to complete questionnaires to provide information on building characteristics that have been reported to affect indoor radon concentrations, such as the house type and size, ventilation and foundations (Borgoni et al., 2014; Demoury et al., 2013). The indoor radon, the period of construction, and the characteristics of the survey houses were evaluated to identify any trends before and after the 2010 NBC was adopted.

2. Methods

A radon survey was conducted in the Canadian cities of Halifax, in the province of Nova Scotia, and Winnipeg, in the province of Manitoba. The approach adopted was to conduct a residential survey of a small geographic area in each city, focussed on neighbourhoods where a substantial number of new dwellings have been built since the year 2000. Halifax and Winnipeg were cities characterized by higher residential radon concentrations in a radon-thoron survey of 33 Census Metropolitan Areas (CMAs) in Canada conducted in 2012–2013 (Chen et al., 2014; Gaskin et al., 2019).

Winnipeg is the capital of the province of Manitoba, Canada, located in the central prairies at the confluence of the Red and the Assiniboine Rivers at a latitude of 49° 53′ N and a longitude of 97° 8′ W. Winnipeg is located at the Southwestern edge of the Canadian Shield, a large geologic continental shield composed primarily of metamorphosed granite. The Red River that flows through Winnipeg formed during the postglacial period, characterized by alluvium that consists of glacial till overlain by glaciolacustrine clays and with a complex upper layer that includes sands, silts, and clays (Gauthier et al., 2022; Lian and Brooks, 2004).

Halifax is the capital of the Eastern Atlantic province of Nova Scotia, Canada, located at a latitude of 44° 39′ N and a longitude of 63° 36′ W. Halifax Harbour opens into the Atlantic Ocean and formed as a result of glacial erosion and subsequent reworking of glacial and lacustrine sediments. A large granitoid complex known as the South Mountain Batholith extends over the Southern part of Halifax Regional Municipality, and has been identified as a region of elevated indoor radon concentrations from prior surveys (Fader and Buckley, 1995; White et al., 2008). The highest soil radon potential values in the Halifax Regional Municipality were calculated for the granulite facies of the glacial tills overlying the South Mountain Batholith, as a result of the highest soil radon gas concentrations and higher soil permeability values measured (O`Brien et al., 2011).

2.1. Survey design

The study design was guided by the recommendations published by the International Atomic Energy Agency (IAEA, 2019). The Halifax and Winnipeg surveys were based on long-term radon measurements obtained during the heating season using alpha-track detectors. Approval was obtained for the study design from the Public Health Agency of Canada/Health Canada research ethics board in July 2021 for the Halifax survey, and from the National Research Council research ethics board in August 2021 for the Winnipeg survey. A postcard campaign offered free radon testing to every house in the target areas, with postcards delivered during November and December 2021, and the first week of January 2022.

The recruitment areas were selected using a commercial mail service that described the buildings served along mail routes, according to characteristics such as building type and period of construction, and are shown in Fig. 1. The survey was conducted in the Northwestern and Northeastern neighbourhoods of Winnipeg and in the Southern part of the Halifax Regional Municipality. All residents in these areas were eligible to participate in the study if they were over 18 years old and living in a detached house, a semi-detached house, or a townhouse built between 2001 and 2021, excluding 2011, the year the new building code provisions were adopted. Houses where post occupancy radon mitigation measures had been implemented were also excluded. The house questionnaires in both the Halifax and Winnipeg surveys collected information about the dates and placement of the radon detectors, whether the house had previously been tested or mitigated for radon, and house characteristics including the year of construction, the house type, the foundation type, the area in contact with the ground and the number of storeys.

Residents interested in participating were directed to a web page that provided detailed information about the radon survey, eligibility criteria, and an email link to the research team. The testing kits included postage-paid envelopes for participants to easily return the detector(s) by mail. Radon testing kits were mailed in November 2021, to 358 participating households in the Halifax survey. Indoor radon measurements and questionnaires were completed by 314 participants (88%) within the study period, of whom 225 met all eligibility criteria. Radon testing kits were mailed at the end of January 2022, to the 284 households who participated in the Winnipeg survey. Indoor radon measurements and house questionnaires were completed by 235 participants (83%) within the study period, of whom 171 met all eligibility criteria.

2.2. Quality assurance and quality control

Participants were instructed to deploy passive alpha track detectors for 91 days: Radtrak^2® detectors were used in the Halifax survey and Radtrak^3® detectors were used in the Winnipeg survey. The Radtrak detectors are based on passive diffusion of radon into pods containing CR-39 film and are suitable for measuring radon from 30 to 50,000 kBqh/m^3 over a duration of 60–365 days. For a measurement duration of 3 months, radon detection ranges from 15 to 25,000 Bq/m^3, with an uncertainty of 6% for 400 kBqh/m^3 (or 200 Bq/m^3 over 3 months).

Unexposed detectors or blanks were included with the detectors received from participants that were mailed to the commercial laboratory for measurement. All fifteen blanks evaluated for the Winnipeg survey were found to have radon concentrations below the detection limit of 15 Bq/m^3. The Halifax study employed field blanks, which were

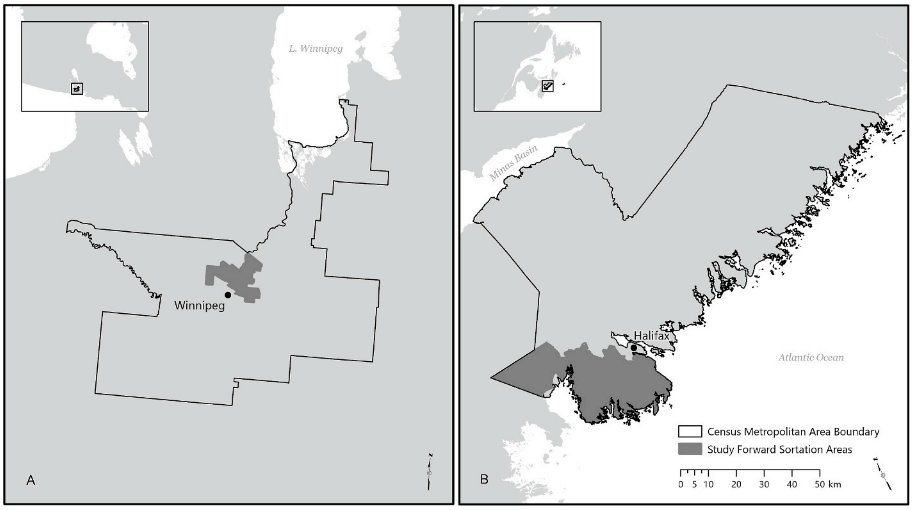

Fig. 1. Recruitment study areas: A) Winnipeg, and B) Halifax.

mailed to and returned by each participant along with the measurement detector, but without opening the original sealed packaging. Eleven of the fourteen field blanks evaluated for the Halifax study had results below the reported detection limits, which ranged from 17 to 23 Bq/m^3, while one was about 50 Bq/m^3, and the remaining two field blanks were under 100 Bq/m^3, corresponding to about one-tenth the concentration reported by the unsealed measurement detectors.

Twenty-seven Halifax study participants were mailed two detectors that were cable-tied together so they were separated by about 5 cm. Thirty Winnipeg study participants were mailed two detectors with instructions asking them to place the detectors about 12 inches apart. Plots of the duplicate results completed for the 24 participants with radon measurements above the detection limit for the Halifax study and the 25 participants in the Winnipeg study are shown in Fig. 2. The median relative percent difference was 6% for the 15 duplicate radon measurements above 200 Bq/m^3 and 30% for the 9 duplicate radon measurements below 200 Bq/m^3 completed by the Halifax participants. The median relative percent difference was 3% for the 4 duplicate radon measurements above 200 Bq/m^3 and 6% for the 21 duplicate radon measurements below 200 Bq/m^3 completed by the Winnipeg participants.

2.3. Analysis

The distribution of radon concentration data was assessed using density histograms and quantile-quantile (QQ) plots of the observed and theoretical quantiles versus the natural logarithm of the measured radon concentrations in QQ. Due to the relatively small sample size, logistic regression modelling was used to evaluate the association between house characteristics and indoor radon. The dependent binary variable was defined as above or below the respective geometric mean indoor radon concentration. Univariate analysis was conducted first using a-priori binary independent variables that characterized differences among the houses recruited from the completed house questionnaires. The characteristics identified in the univariate analyses by $p < 0.25$ were included in the multivariate logistic regression (Eq. (1)). A 95% uncertainty interval was determined for the odds ratio associated with each statistically significant variable in the multivariate logistic regression. The likelihood ratio test was used to select the preferred model from nested models having fewer predictors, with the null hypothesis being that the full and nested models fit the data equally well.

$$ln\{p(X) / [1 - p(X)]\} = \propto + \sum \beta_i X_i \quad \text{(eq. 1)}$$

The estimation of statistical power and sample size for logistic regression was based on the Wald significance testing (Demidenko, 2007). Assuming a single binary independent variable in addition to the binary dependent variable, a lower bound for the sample size for the common scenario defined by alpha of 0.05 and power of 0.8, is given Eq. (2):

$$n \geq {}^{125}/{}_{\beta^2} \quad \text{(eq. 2)}$$

Unlike linear regression, an independent confounder in addition to the variable of interest may improve the study power for logistic regression (Demidenko, 2007; Hsieh, 1989). The statistical power of the analyses was optimized by using the geometric mean to define the binary dependent variable.

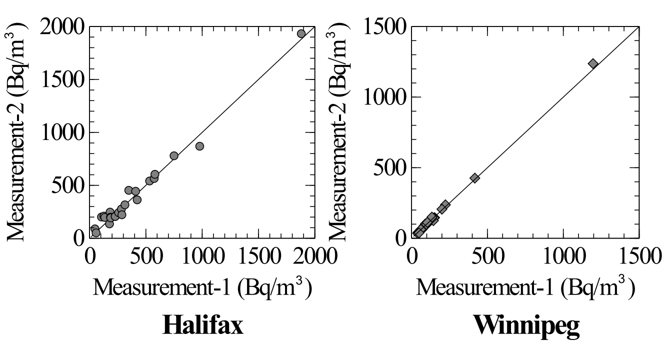

Fig. 2. Duplicate radon measurements for study houses in Halifax and Winnipeg.

3. Results

3.1. House characteristics

The main characteristics of the houses of the participants recruited in the Halifax and Winnipeg studies were summarized in Table 1 by decade of construction. The majority of the participants recruited lived in detached houses in both cities and construction periods: 92% (121/132) and 88% (82/93) for the earlier and later construction periods in the Halifax study, and 98% (82/84) and 80% (70/87) in the Winnipeg study. Most of the houses in both cities and construction periods had a finished basement. Houses with 2–3 storeys above ground were more common than bungalows, representing about two-thirds of those in the Winnipeg study and about 70–80% of those in the Halifax study. Most participants provided information regarding the floor where the radon

Table 1
Summary of house characteristics.

House characteristic	Halifax	Halifax	Winnipeg	Winnipeg
Construction year	2001–2010	2012–2021	2001–2010	2012–2021
Total	132	93	84	87
House Type:				
detached	121	82	82	70
semi-detached/ townhouse	11	11	2	17
Foundation:				
Full basement	102	63	84	82
Split-level, slab on grade/crawl space	30	30	0	5
Number of floors (excluding basement):				
1	15	16	27	32
2 or 3	106	66	57	54
other/not reported	11	11		1
Floor detector was placed:				
basement	77	51	55	40
First (main)/second floor	55	42	29	41
not reported				6
Area in contact with the ground:				
$\leq$ 1000 ft^2	69	55	46	46
>1000 ft^2	62	37	30	32
not reported	1	1	8	9
Heating type			NA	NA
Forced-air furnace	16	5		
heat pump/radiant/ baseboard/wood stove	116	88		
Heat recovery ventilation (HRV)			NA	NA
yes	38	12		
no	94	81		
Water source			NA	NA
municipal	46	44		
well	86	49		

detector was located and an estimate of the area of the house in contact with the ground (reported in square feet and therefore presented using this unit). More than half of the radon detectors were placed in the basement, and on the first (main) floor in most of the remaining houses, for both periods of construction in Halifax and in Winnipeg. There was a fairly even split between houses having a ground contact area above and below 1000 square feet in both cities and construction periods, with a slightly higher proportion of homes having a larger footprint.

The survey in Halifax Regional Municipality included urban houses connected to a municipal water supply and country houses using well water, and participants reported using a range of primary heating systems that included forced-air furnaces, heat pumps, wood stoves or fireplaces, in-floor radiant heating, electric baseboard, and hydronic systems. The survey in Winnipeg was focussed in new housing developments in the suburbs, where houses predominantly had forced-air furnaces for heating and were connected to the municipal water supply. Responses to questions about the ventilation systems installed in the houses of participants recruited in Winnipeg were incomplete.

3.2. Radon measurements

The majority of the study houses in both Halifax and Winnipeg studies were detached houses, and represented 92% and 98%, respectively, of the houses built between 2001 and 2010. The analysis was focused on detached houses, for which the sample size of 203 for the Halifax study and 153 for the Winnipeg study provided sufficient statistical power to evaluate trends in indoor radon during the period that included the decade before and after the 2011 adoption of the provincial building code change. The summary statistics of the radon distributions for the detached houses in the Halifax study and the Winnipeg study are provided in Table 2. The box and whisker plots in Fig. 3 show that the indoor radon concentrations were higher for the detached houses in the Halifax study than in the Winnipeg study, with an arithmetic mean of 361 Bq/m^3 and a maximum value of 1880 Bq/m^3 for the Halifax study and an arithmetic mean of 149 Bq/m^3 and a maximum value of 1217 Bq/m^3 for the Winnipeg study. The distributions of radon measurements for both the Halifax and Winnipeg studies both had a typical lognormal shape, having an arithmetic mean greater than the median value, and a long tail of higher radon concentrations.

Table 2
– Summary of radon measurements in detached houses in the Halifax and Winnipeg surveys.

Radon distribution parameter	Halifax: detached houses	Winnipeg: detached houses
Number	203	151
Average test duration (days)	96	92
Arithmetic mean (Bq/m^3)	361	149
Geometric mean (Bq/m^3)	247	118
Geometric standard deviation	2.5	2.0
Maximum (Bq/m^3)	1880	1217
Minimum (Bq/m^3)	19	22

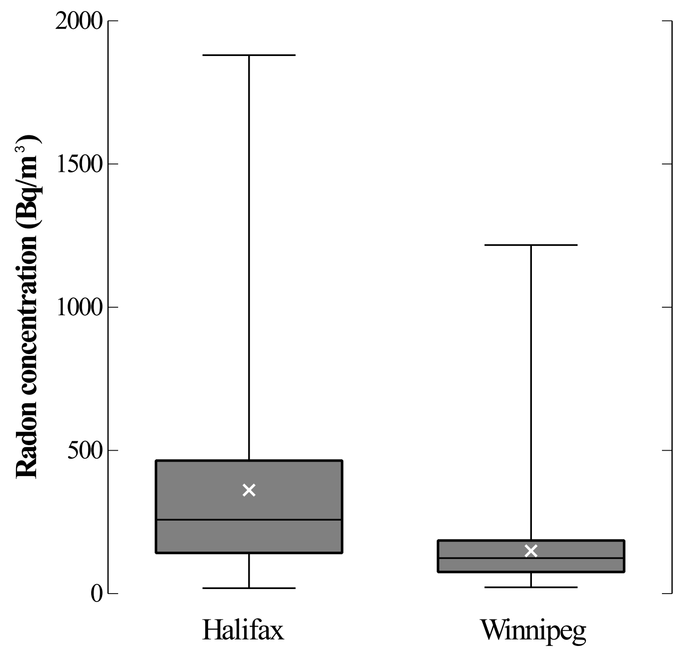

Fig. 3. Box and whisker plots of the radon distributions for detached study houses for Halifax and Winnipeg.

The density histograms showed positive skewness for the distributions of both the Halifax and Winnipeg survey houses, shown in Figs. 4 and 5, respectively. Three quarters (152/203) of the detached houses in the Halifax study and one in five (31/151) of those in the Winnipeg study had an indoor radon concentration above the Canadian guideline value for existing housing of 200 Bq/m^3. The observed and theoretical quantiles were plotted versus the natural logarithm of the measured radon concentrations in the normal Q-Q plots for the Halifax survey houses and the Winnipeg survey houses, shown in Figs. 4 and 5, respectively. The plots of the observed quantiles were very close to linear and matched the theoretical quantiles for the main body of both distributions, supporting the fit of the lognormal distribution. The geometric mean (geometric standard deviation) was 247 (2.5) Bq/m^3 for the detached houses in the Halifax study and 118 (2.0) Bq/m^3 for the detached houses in the Winnipeg study (Table 2).

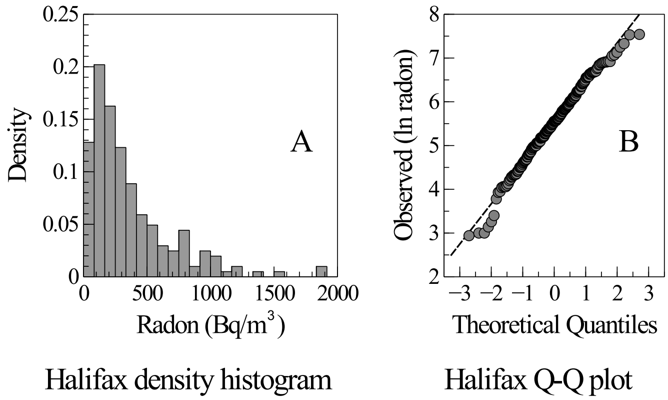

Fig. 4. Measured radon concentration in the detached houses for the Halifax study: A) Density histogram, and B) Q-Q plot of the observed and theoretical cumulative distributions for the log-transformed values of radon concentration.

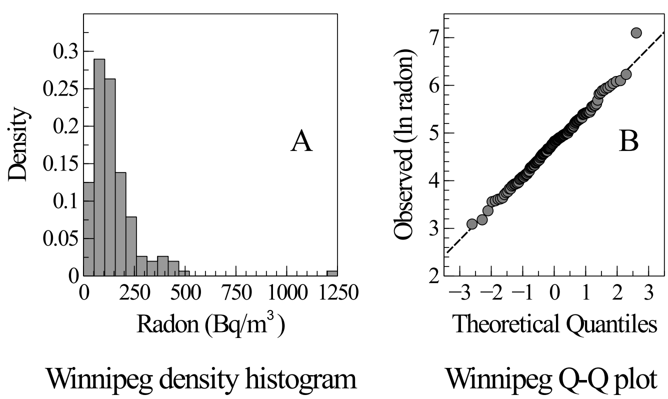

Fig. 5. Measured radon concentration in the detached houses for the Winnipeg study: A) Density histogram, and B) Q-Q plot of the observed and theoretical cumulative distributions for the log-transformed values of radon concentration.

3.3. *Logistic regression analyses*

Logistic regression analyses were conducted to evaluate the factors associated with higher indoor radon concentration for the detached houses in the Halifax study and for the detached houses in the Winnipeg study. The binary dependent variable was defined for each study site by the geometric mean indoor radon concentration because they were both lognormally distributed.

Table 3
– Binary independent variables used in logistic regression analyses.

Binary variable	value	description
House type	0	semi-detached or townhouse
	1	Detached house
Period built	0	2001–2010
	1	2012–2021
Detector location	0	Basement
	1	First (main)/second floor
Ground contact area	0	≤ 1000 sq ft
	1	>1000 sq ft
Storeys	0	1 storey above ground
(excluding basement)	1	2 or 3 storeys above ground
HRV	0	no HRV
	1	HRV
Heating type	0	Forced-air furnace
	1	other
Water source	0	municipal
	1	well
Foundation type	0	Full basement
	1	other

Binary independent variables were also defined in Table 3 where sufficient data was available. Binary independent variables included the period the house was built, the floor where the radon detector was located, the area of the house in contact with the ground, and the number of storeys above ground. (Table 3). A binary variable defining the area in contact with the ground as above and below 1000 square feet was selected because the reported values mostly rounded off to the nearest 100 square feet. The logistic regression analyses for the Halifax study also included binary independent variable for presence of a heat recovery ventilation system (HRV), heating type (defined as forced air furnace or other heating system), water source (defined as municipal supply or well water), and foundation type (defined as full basement or other: split-level, slab-on-grade, or crawl space).

3.3.1. *Trends in radon for detached houses halifax*

Univariate logistic regression analyses were conducted to evaluate whether there was any association with the indoor radon concentration for each independent variable described in Table 3 for the detached houses in the Halifax study. The results of the univariate logistic regression analyses are listed in Table 4 and show that only the floor upon which the radon detector was located had a significant association, at an alpha of 0.05, with having a higher indoor radon concentration. A multivariate logistic regression was conducted for the detached houses in the Halifax study that included all the independent variables identified by a p value less than 0.25 in the univariate regression and that were potentially associated with the indoor radon concentration (model 1). The results of the multivariate logistic regression model 1 that included the period of construction, the floor the detector was located, the water source and presence of an HRV system are listed in Table 5. A statistically significant association was identified for both the period of construction and the floor the detector was located. The nested model shown in Table 5 as model 2 was preferred because likelihood ratio testing demonstrated that the extra variable in model 1 does not significantly improve the model fit ($p = 0.47$). For the detached houses in the Halifax study, an odds ratio of 1.91 (1.04–3.50) for a construction year after 2011 ($p = 0.033$) and an odds ratio of 0.48 (0.27–0.86) for measurement on an upper floor ($p = 0.012$) were associated with having a higher than geometric mean radon concentration.

3.3.2. *Trends in radon for detached houses winnipeg*

Univariate logistic regression analyses were conducted to evaluate whether there was any association of the period built, the floor the detector was located, ground contact area, or the number of storeys above the ground with the indoor radon concentration for the detached houses in the Winnipeg study. The results of the univariate logistic regression analyses are listed in Table 6 and show that only the floor upon which the radon detector was located had a significant association, at an alpha of 0.05, with having a higher indoor radon concentration. A multivariate logistic regression was conducted for the detached houses in the Winnipeg study that included all the independent variables identified by a p value less than 0.25 in the univariate regression and that were potentially associated with the indoor radon concentration (model A). The results of the multivariate logistic regression model A that included the period of construction, the floor the detector was located, and the number of storeys above ground are listed in Table 7, with the period of construction included because it was a variable of particular interest. The floor the detector was located was found to be close to statistical significance, and was significant when it was the only independent variable included in the analysis. The nested model shown in Table 7 as model B was preferred because likelihood ratio testing demonstrated that the extra two variables in model A do not significantly improve the model fit ($p = 0.73$). For the detached houses in the Winnipeg study, an odds ratio of 0.45 (0.32–0.64) for measurement on an upper floor was associated with having a higher than geometric mean radon concentration ($p = 0.022$).

Table 4
– Univariate logistic regression analyses for detached houses Halifax.

Logistic regression	Log-likelihood	df	Model parameter	β estimate	Standard error	Z value	Pr(>|z|)
Detector location	−137.32	2	intercept	0.4583	0.1948	2.352	0.019[a]
			floor = 1	−0.6766	0.2863	−2.363	0.018[a]
Ground contact area	−139.24	2	intercept	0.2318	0.1974	1.174	0.240
			ground contact area = 1	−0.1501	0.2826	−0.531	0.595
Storeys	−140.12	2	intercept	0.0645	0.3594	0.180	0.857
			storeys = 1	0.0986	0.3906	0.252	0.801
Period_built	−138.68	2	intercept	−0.0496	0.1819	−0.273	0.785
			period_built = 1	0.4959	0.2904	1.708	0.088
HRV	−139.10	2	intercept	0.0382	0.1597	0.239	0.811
			HRV = 1	0.4959	0.3447	1.439	0.150
Heating type	−139.59	2	intercept	−0.3185	0.4646	−0.685	0.493
			heating = 1	0.5147	0.4877	1.055	0.291
Water source	−139.25	2	intercept	0.4177	0.2478	1.685	0.092
			water = 1	−0.4029	0.3018	−1.335	0.182
Foundation	−140.02	2	intercept	0.1951	0.1675	1.165	0.244
			FoundT = 1	−0.1612	0.3096	−0.521	0.603

Note.
[a] indicates significance at $\alpha = 0.05$, df – degrees of freedom.

Table 5
– Multivariate logistic regression modelling for detached houses Halifax.

#	Model logLikelihood	df	Parameter	Estimate of β	Standard error	z-value	P>|z|	Odds Ratio
1	−133.56	5	(intercept)	0.2254	0.3189	0.707	0.4796	
			period built = 1	0.6198	0.3060	2.025	0.0428[a]	1.86 (1.01–3.43)
			floor = 1	−0.7012	0.2970	−2.361	0.0182[a]	0.50 (0.27–0.90)
			waterS = 1	−0.2298	0.3158	−0.728	0.4667	
			HRV = 1	0.6716	0.3598	1.867	0.0619	
2	−133.82	4	(intercept)	0.0764	0.2436	0.314	0.7538	
			period built = 1	0.6464	0.3037	2.129	0.0333[a]	1.91 (1.04–3.50)
			floor = 1	−0.7369	0.2931	−2.515	0.0119[a]	0.48 (0.27–0.86)
			HRV = 1	0.6749	0.3592	1.879	0.0602	

Note.
[a] indicates significance at $\alpha = 0.05$, df – degrees of freedom.

Table 6
– Univariate logistic regression analyses for detached houses Winnipeg.

Logistic regression	Log-likelihood	df	Model parameter	β estimate	Standard error	Z value	Pr(>|z|)
Period built	−105.11	2	intercept	0.1466	0.2215	0.662	0.508
			period built = 1	−0.1756	0.3271	−0.537	0.591
Detector location	−98.47	2	intercept	0.3594	0.2142	1.678	0.0934
			floor = 1	−0.7947	0.3475	−2.287	0.0222[a]
Ground contact area	−94.13	2	intercept	0.1054	0.2653	0.397	0.691
			ground contact area = 1	−0.0294	0.3480	−0.084	0.933
Storeys	−103.64	2	intercept	0.3610	0.2716	1.329	0.184
			storeys = 1	−0.4664	0.3406	−1.369	0.171

Note.
[a] indicates significance at $\alpha = 0.05$, df – degrees of freedom.

Table 7
– Multivariate logistic regression modelling for detached houses Winnipeg.

#	Model logLikelihood	df	Parameter	Estimate of β	Standard error	z-value	P>|z|	Odds Ratio
A	−86.84	4	(intercept)	0.5651	0.3383	1.671	0.0948	
			period built = 1	−0.1912	0.3505	−0.546	0.5854	
			floor = 1	−0.6969	0.3700	−1.884	0.0596	
			storeys = 1	−0.2556	0.3758	−0.680	0.4964	
B	−87.07	2	intercept	0.3594	0.2142	1.678	0.0934	
			floor = 1	−0.7947	0.3475	−2.287	0.0222[a]	0.45 (0.32–0.64)

Note.
[a] indicates significance at $\alpha = 0.05$, df – degrees of freedom.

4. Discussion

The majority of the participants recruited in the Halifax and Winnipeg studies lived in detached houses and the analysis was, therefore, focussed on the characteristics of the detached study houses. The indoor radon concentrations were higher in the Halifax study than in the Winnipeg study, and lognormally distributed in both. The indoor radon in the detached houses was characterized by a geometric mean (geometric standard deviation) of 247 (2.5) Bq/m^3 in the Halifax study and 118 (2.0) Bq/m^3 in the Winnipeg study. Three quarters of the detached houses in Halifax and one in five in Winnipeg had an indoor radon concentration above the Canadian guideline value for existing housing of 200 Bq/m^3, with maximum values of 1880 Bq/m^3 for Halifax and 1217 Bq/m^3 for Winnipeg. Significant associations were identified for the period of construction and the floor where the radon detector was located in the multivariate logistic regression analyses. An odds ratio of 1.91 (1.04–3.50) for the detached Halifax study houses built after 2011 was associated with having a radon concentration above the geometric mean ($p = 0.033$), nearly double the likelihood. A lower likelihood – almost half - for measurement conducted on a main/upper floor compared to in the basement was associated with having a radon concentration above the respective geometric mean for each city: an odds ratio of 0.48 (0.27–0.86) for the detached Halifax study houses ($p = 0.012$), and of 0.45 (0.32–0.64) for the detached Winnipeg study houses ($p = 0.022$).

The geometric mean radon concentration of 118 Bq/m^3 for the detached study houses recruited in neighbourhoods on the outskirts of Winnipeg was between the value of 100 Bq/m^3 reported for the province of Manitoba and of 199 Bq/m^3 reported for Winnipeg, in the Cross Canada Survey of Radon and the CMA survey (Chen et al., 2014; Gaskin et al., 2019; Health Canada, 2012). The geometric mean indoor radon of 247 Bq/m^3 for the detached study houses was higher than the value of 91 Bq/m^3 reported for the Halifax Regional Municipality in the CMA survey, which is consistent with the study houses being recruited in the known geologic high radon zone within this area (O'Brien et al., 2011). The indication of a significant trend of higher indoor radon in detached Halifax study houses built during the decade after the adoption of the 2010 NBC radon provisions, relative to the decade before, was consistent with a descriptive summary published by Health Canada that reported almost double the percentage of houses with a radon concentration above 600 Bq/m^3 (14%–27%) and a decrease in the percentage of these Halifax study houses below 200 Bq/m^3 (44%–33%) during the same time frame (Health Canada, 2022). A large ongoing indoor radon survey conducted in Canada has reported a substantial increase leading to the highest mean concentration for houses built during the most recent decade in the Prairie provinces that include Manitoba, Saskatchewan and Alberta, but more stable mean concentrations for the central and Atlantic region and the North and Pacific region (Khan et al., 2021). Indoor radon has also been reported to be significantly higher when measured in basements than on upper floors (Borgoni et al., 2014; Demoury et al., 2013; Stanley et al., 2019).

The World Health Organisation has reviewed the reported effectiveness of radon preventive measures commonly used in new construction to reduce population exposure (WHO, 2009). Sealing soil contacted surfaces was reported to have no to low/moderate radon reduction and poor to fair long-term performance. As only increasing the sealing as required in the 2010 NBC radon provisions to the pre-existing damp-proofing requirement for a 150 μm-thick polyethylene foundation membrane would have had the potential to further reduce radon ingress, the association of higher indoor radon for detached houses built after the adoption of this building code change in 2011 in the Halifax study and the finding of no significant trend for the detached houses in the Winnipeg study were consistent with the WHO report. Although the pipe stub required in the 2010 NBC radon provisions would not reduce radon ingress in new construction, it could facilitate post-occupancy testing and mitigation - as recommended by the WHO to reduce the risk for those exposed to the highest concentrations - if an active or passive depressurization were constructed using the pipe stub as a starting point.

Despite the relatively small sample sizes for both the Halifax and Winnipeg studies, statistically significant independent variables were identified based on the Wald statistic in the multivariate logistic regressions. A strength of these studies was that they were designed to recruit participants from a small geographic area within each city to reduce variation in geogenic radon potential and more clearly identify house characteristics associated with indoor radon concentration. Long-term radon measurements, with an average test duration of 92–96 days, were conducted during a four-month period during the heating season in each city to avoid the effect of natural year-to-year variation in radon, and the participants surveyed reported opening windows infrequently. In Halifax, the average monthly temperature was below zero and snow was present on the ground for three of the four months during the study period, with average monthly temperature ranging from - 4 °C to 7 °C (Environment and Natural Resources Canada, 2024). In Winnipeg, the average monthly temperature was below zero and snow was present on the ground for three of the four months during the study period, with average monthly temperature ranging from - 20 °C to 11 °C. The survey did rely on voluntary participation, but to reduce selection bias, every household living in the target areas (instead of a sample) was invited to participate. Additionally, to reduce barriers to participation, there was no cost for residents and testing kits were mailed that included postage-paid envelopes for the return of the detector and the questionnaire. However, the ventilation systems could not be well characterized due to participants reporting limited knowledge of the details of their heat recovery ventilation systems. It has been noted that accurate evaluation of the air exchange rate in a field study requires tracer gas testing in each house (Bräuner et al., 2013).

It was assumed that there was minimal confounding with respect to energy efficiency of the low-rise dwellings recruited in this survey because the prescriptive requirements for housing and small buildings described in Part 9 of the NBC have remained consistent during the period the study houses were built. A tiered approach has been introduced in the prescriptive and performance paths in the NBC 2020 published in 2022 (Canadian Commission on Building, Fire Codes, 2022), representing a significant change that enables provincial and municipal authorities having jurisdiction the flexibility to increase energy efficiency requirements (Gilani et al., 2023). In addition, this study was restricted to houses built relatively recently, after the year 2000, and are less likely to have undergone energy retrofits than older housing stock. Evaluating any impacts on indoor radon concentrations for the range of options available to improve energy efficiency that can be implemented in new housing or retrofitted in existing housing is a subject of increasing interest and future research in Canada.

Lung cancer is the most common cause of cancer death in Canada, and it was reported that although the age standardized incidence rate (ASIR) for men had decreased following the reducing in smoking prevalence, the ASRI for women had not decreased in 9 of 12 provinces and territories between 1992 and 2016 (Canadian Cancer Society Advisory Committee, 2020). Tobacco and radon are the two most important causes of lung cancer in Canada, and while smoking prevalence has steadily decreased (Pelekanakis et al., 2021), recent surveys indicate that the increased membrane sealing measures in the 2010 NBC were insufficient and that residential radon exposures have yet to be reduced. The results of this study support strengthening the radon preventive measures required in new low-rise housing to reduce the associated lung cancer burden in Canada. The studies in Norway and Finland have demonstrated that vertical passive depressurization stacks have been robust when implemented in housing built according to standard construction and inspection procedures. In February 2024, the Canadian Board for Harmonized Construction Codes presented the Proposed Change 1713 to the NBC for review by the public, which would require a passive vertical radon stack in new low-rise residential dwellings where the floor separates a conditioned space from the ground (Canadian

Board for Harmonized Construction Codes, 2024).

5. Conclusions

The majority of the participants recruited in the Halifax and Winnipeg studies lived in detached houses and the indoor radon concentrations measured were lognormally distributed. The indoor radon in the detached study houses built after the year 2000 were characterized by a geometric mean (geometric standard deviation) of 247 (2.5) Bq/m^3 in the Halifax study and 118 (2.0) Bq/m^3 in the Winnipeg study. Significant associations were identified for the period of construction and the floor where the radon detector was located in the multivariate logistic regression analyses. An odds ratio of 1.91 (1.04–3.50) indicated almost double the likelihood of having an indoor radon concentration above the geometric mean for the detached Halifax study houses built after 2011, when the 2010 NBC building code was adopted by the province. There was no evidence of any significant change in the indoor radon after 2011 in the detached Winnipeg study houses. Radon is the second leading cause of lung cancer, after smoking, and the results of this study support strengthening the radon preventive measures required in new low-rise housing, such as those currently under review by the National Building Code of Canada, to reduce the associated lung cancer burden in Canada.

CRediT authorship contribution statement

Janet Gaskin: Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Liang Grace Zhou:** Writing – review & editing, Funding acquisition. **Robert Stainforth:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Colin Gutcher:** Visualization. **Pawel Mekarski:** Writing – review & editing. **Roshini Kassie:** Methodology. **Karen Li:** Investigation, Data curation. **Ngoc Vuong:** Investigation. **Jeff Whyte:** Writing – review & editing. **Michel Gauthier:** Methodology, Funding acquisition. **Debora Quayle:** Writing – review & editing.

Declaration of competing interest

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

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Data availability

Maintaining the confidentiality of the individual residential radon measurements for study participants was required to obtain the Research Ethic Board approval of the study protocol.

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