

A Summary of Residential Radon Surveys and the Influence of Housing Characteristics on Indoor Radon Levels in Canada

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Abstract—Based on community and nationwide radon surveys with long-term radon measurements in a total of 21,818 homes, radon distribution characteristics in Canada have been reassessed with the population-weighted arithmetic mean radon concentration of 82 Bq m⁻³, geometric mean radon concentration of 55 Bq m⁻³, and geometric standard deviation of 2.45. The major pathway for the influx of radon into Canadian homes is from the surrounding soil. Statistical analysis has shown that radon levels in houses with a basement are, on average, about twice the radon levels in houses without a basement, and houses with private wells also tend to have higher radon concentrations than houses with municipal water supply.

Health Phys. 121(6):574–580; 2021

Key words: ²²²Rn; ²²²Rn, indoor; health effects; radioactivity, indoor

INTRODUCTION

RADON (²²²Rn) is a naturally occurring radioactive gas generated by the decay of uranium-bearing minerals in rocks and soils. It has been well known for decades that exposure to radon and its short-lived progenies in the air has been identified as the second leading cause of lung cancer after tobacco smoking (NAS/NRC 1999; WHO 2009; UNSCEAR 2009; ICRP 2010, 2014). To establish the geographical variation of radon, the first cross-Canada radon survey was carried out between June and August during 1977, 1978, and 1980 in roughly 14,000 homes in 19 cities (Letourneau et al. 1984, 1992). In that survey, a single grab sample was taken in basement locations where basements were present or on the main floor for houses without a basement. The observed radon

concentrations in the 14,000 Canadian homes followed a log-normal distribution with the population-weighted geometric mean (GM) radon concentration of 11.2 Bq m⁻³, geometric standard deviation (GSD) of 3.9, and arithmetic mean (AM) radon concentration of 28.4 Bq m⁻³ (Letourneau et al. 1992). The results indicated that there is a distinct and statistically valid difference in radon concentration in homes in different Canadian cities. Since then, more residential radon surveys with long-term radon testing using alpha track detectors have been conducted in various communities across Canada. Following the revision of the Canadian radon guideline from 800 to 200 Bq m⁻³ in June 2007 (Health Canada 2007), the second cross-Canada radon survey was conducted during the heating season from 2009 to 2011 in roughly 14,000 homes in all 121 health regions (Health Canada 2012). With the additional and more accurate information, an update on radon exposure in Canada is provided here.

In Canada, the major pathway for the influx of radon into a home is from the surrounding soil. A study of 33 households in a small township showed that indoor radon concentrations can differ significantly for houses located on the same street (McGregor et al. 1985). Early in the first cross-Canada radon survey (Letourneau et al. 1984), influence of Canadian-specific housing characteristics on the indoor radon concentration (such as house type, external housing material, heating system, basement type, basement windows, basement sump, and age of home) was considered. While geographic variation of radon concentration was clearly observed among 19 cities surveyed, analysis of all the housing factors failed to show any correlation between radon levels and housing factors except in the case of open basement windows vs. closed basement windows (McGregor et al. 1980). However, the study on the influence of geological and housing characteristics on indoor radon levels in 894 residences of the province of Quebec (Levesque et al. 1997) showed that geological factors only explain 5% and 4.5% of the variations in ²²²Rn concentrations in the basement and on the first floor, respectively, while housing characteristics explain 18% and 15% of the variations in ²²²Rn concentrations in the basement and on the first floor. A recent study in 1,135

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The author declares no conflicts of interest.

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(Manuscript accepted 5 June 2021)

0017-9078/21/0

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DOI: 10.1097/HP.0000000000001469

homes in southern Alberta found that homes built in 1992 or later had radon levels 31.5% higher, on average, than older homes (Stanley et al. 2017). To further study the influence of housing characteristics on indoor radon concentration, survey questionnaires similar to those used in the first cross-Canada radon survey (Letourneau et al. 1984) were distributed to all participating households in the second cross-Canada radon survey (Health Canada 2012). With the newer information, the influence of housing characteristics on indoor radon levels was analysed, and the results are summarized here.

DATA AND METHODS

Health Canada recommends the placement of at least one long-term detector in a home for a minimum of 3 to 12 mo (12 mo is optimal). For periods less than 12 mo, the testing period should include a mix of seasons or be in a mid-season to best provide a measurement that reflects the annual average level. The ideal 3-mo testing period would be in the typical heating season that runs from October through April (Health Canada 2008). In this summary, only long-term radon measurements are considered. Surveys identified for this summary are listed in Table 1. All community radon surveys followed Health Canada's guide for Radon Measurements in Residential Dwellings (Health Canada 2008). There are two large-scale national surveys, the 2009-2011 national radon survey carried out in roughly 14,000 homes in 121 health regions across Canada (Health Canada 2012) and simultaneous radon and thoron surveys in 33 Canadian cities for about 4,000 homes in 2011-2012 (Chen et al. 2015). Combined with several community-specific radon surveys in the recent decade (Chen et al. 2008, 2009, 2010, 2011; Dessau et al. 2004; BCLA 2014a and b; Stanley et al. 2017), a total of 21,818 homes were tested for radon.

Canada is a vast country; however, most of the population lives on a small portion of the land. In recent decades, there has been an increasing demand for relevant health information at a community level. As a result, health regions have become an

important geographic unit by which health and health-related data are produced (<https://www150.statcan.gc.ca/n1/pub/82-402-x/2015001/regions/hrpg-eng.htm>). The geographic size of a health region depends partly on population. There are more health regions in areas of high population density. In the far north where population density is very low, a health region can cover a very large geographic area, as shown in Fig. 1.

The most recent cross-Canada radon survey was designed to gather long-term (3 mo or longer) indoor radon test results in all health regions in Canada (Health Canada 2012). In this study, radon measurement data collected from various surveys as listed in Table 1 are grouped by health regions. Sample-weighted average radon concentrations and associated standard deviations were derived for each health region. Population weighting is then applied to calculations for average values for province/territory and the entire country of Canada.

In the recent cross-Canada radon survey (Health Canada 2012), each participant household received a questionnaire to complete with their radon detector package. The questionnaire was designed to provide additional detail on the home in order to allow Health Canada to determine whether the radon levels measured were related to a particular home's construction or ventilation system. In the survey, each household only received one detector with instructions to place it in the lowest level of a house where occupants spend at least 4 h d⁻¹. Since detector location can also influence the radon test result in a house, the statistical analysis on the influence of housing characteristics on indoor radon concentration is mainly descriptive. The following housing characteristics are analyzed here: age and type of house, heating system, basement characteristics, and water system.

RESULTS

Summary of residential radon distribution in Canada

Since radon in indoor environment is lognormally distributed, its distribution can be best described by the geometric mean (GM) and geometric standard deviation (GSD).

Table 1. Residential radon surveys carried out in the recent decade.

Survey area	Number of households with valid results	Range, Bq m ⁻³	Reference
121 health regions in Canada	13,807	(15-5,657)	Health Canada 2012
33 metropolitan areas in Canada	3,215	(10-2,117)	Chen et al. 2015
Capital city of Ottawa	95	(8-1,525)	Chen et al. 2008
City of Winnipeg, Manitoba	116	(20-483)	Chen et al. 2009
City of Fredericton, New Brunswick	45	(16-1,374)	Chen et al. 2011
City of Halifax, Nova Scotia	65	(4-2,341)	Chen et al. 2011
Mont Laurier, Quebec	50	(16-773)	Chen et al. 2010
15 regions in Quebec	449	(10-10,500)	Dessau et al. 2004
Prince George, British Columbia	1,436	(15-1,380)	BCLA 2014a
Castlegar, British Columbia	158	(15-1,250)	BCLA 2014b
South Alberta	2,382	(15-3,441)	Stanley et al. 2017
Total	21,818	(4-10,500)	This study

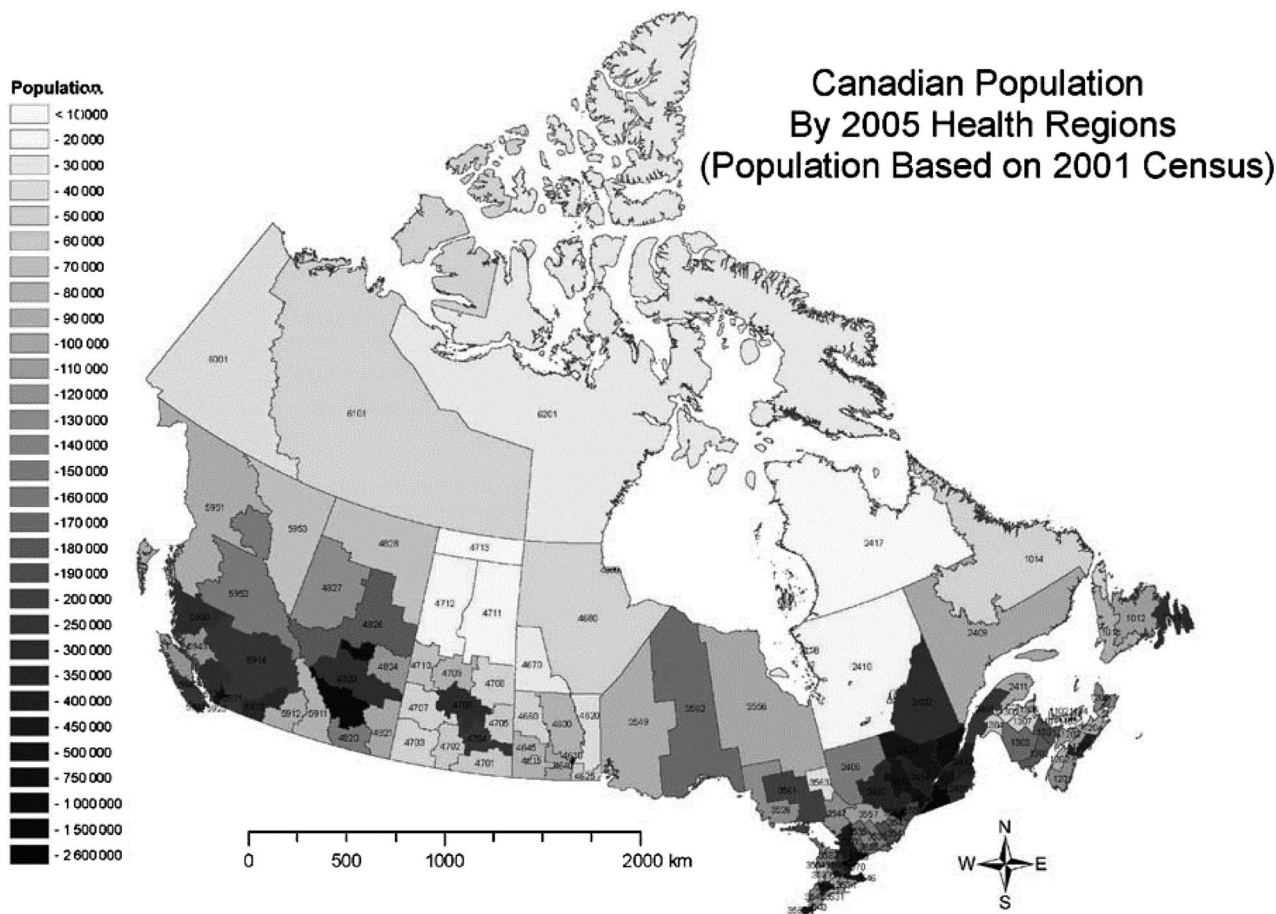


Fig. 1. Health regions in Canada 2005 (Statistics Canada 2005).

Combining all data from previous national and community-specific surveys as listed in Table 1 (BCLA 2014a and b; Chen et al. 2008, 2009, 2010, 2011, 2015; Dessau et al. 2004; Health Canada 2012; Stanley et al. 2017), radon distribution characteristics [population-weighted GM, GSD,

and arithmetic mean (AM)] are recalculated by province and territory, as given in Table 2. Weighted again by population, the radon distribution in Canadian homes has a GM of 55 Bq m⁻³ with a GSD of 2.45. The population-weighted AM is 82 Bq m⁻³.

Table 2. Population-weighted radon concentrations (Bq m⁻³) in residential homes by province and territory.

	Population in 2019	Samples	GM	GSD	AM
British Columbia (BC)	5,071,336	3,809	33	2.06	47
Alberta (AB)	4,371,316	3,709	93	1.77	108
Saskatchewan (SK)	1,174,462	1,406	114	2.21	153
Manitoba (MB)	1,369,465	1,400	124	2.44	174
Ontario (ON)	14,566,547	5,458	45	2.50	69
Quebec (QC)	8,484,965	2,780	47	2.72	79
New Brunswick (NB)	776,827	1,086	73	3.36	151
Prince Edward Island (PEI)	156,947	113	24	2.94	46
Nova Scotia (NS)	971,395	759	55	3.49	130
Newfoundland and Labrador (NL)	521,542	810	41	2.91	71
Yukon (YK)	40,854	225	87	3.06	175
Northwest Territories (NWT)	44,826	185	39	3.01	69
Nunavut (NU)	38,780	78	9.3	1.48	10
Canada	37,589,262	21,818	55	2.45	82

Table 3. Radon distribution characteristics by year residence was built.

Year residence was built	N	GM (Bq m ⁻³)	GSD	AM (Bq m ⁻³)
Before 1920	906	25	4.35	75
1921-1945	777	40	2.89	71
1946-1960	1,626	47	3.03	87
1961-1970	1,729	51	3.12	97
1971-1980	2,906	55	3.07	103
1981-1990	2,190	47	3.50	103
1991-2000	1,790	49	3.28	99
2001-2010	1,446	57	3.18	111

Influence of housing characteristics

In the 2009–2011 cross-Canada radon survey (Health Canada 2012), each participating household received questionnaires on housing characteristics to complete with their radon detector package. The overall completion rate for the questionnaires was approximately 77%. Information on housing characteristics and the influence on indoor radon level are summarized here.

Age and type of house

Summary information on age of house and the average radon levels for houses built in different time periods are given in Table 3 and graphically shown in Fig. 2. It can be seen that radon concentrations are generally higher in newer homes than in older homes. The trend that GMs are higher in

newer homes is statistically significant (ANOVA, $F_{1,7} = 17.02$, $R^2 = 0.74$, $p = 0.0062$). There are a total of 3,309 houses built before 1960 with an overall average GM of 39.4 Bq m⁻³ and GSD of 3.36. For a total of 10,061 houses built after 1960, the average GM is 51.8 Bq m⁻³ with a GSD of 3.22. Under similar GSDs, the average GM value in newer houses is 30% higher than the average GM value in old houses.

Information on mean radon concentrations in different types of houses is summarized in Table 4. For single-detached houses, there are 5,382 bungalows with an average GM of 62 Bq m⁻³ and a GSD of 3.11. There are a total of 6,216 single-detached houses with multiple stories. Those multi-story houses have an average GM of 42.7 Bq m⁻³ and a GSD of 3.28. Under similar GSDs, the average GM value in bungalows is 46% higher than the average GM in multi-story single-detached houses. The survey tested a total of 640 houses of multi units. The average GM for multi units is 25.1 Bq m⁻³ with a GSD of 3.34. With slightly wider variation (slightly large GSD), the average GM value in multi-family units is significantly lower than in single-detached houses, 70% lower than in multi-story single-detached houses, and a factor of 2.5 lower than in bungalows. Trailer mobile homes have the lowest radon concentration, on average.

Heating system

Due to the cold climate in Canada, heating systems are present in all households. The 2009–2011 cross-Canada

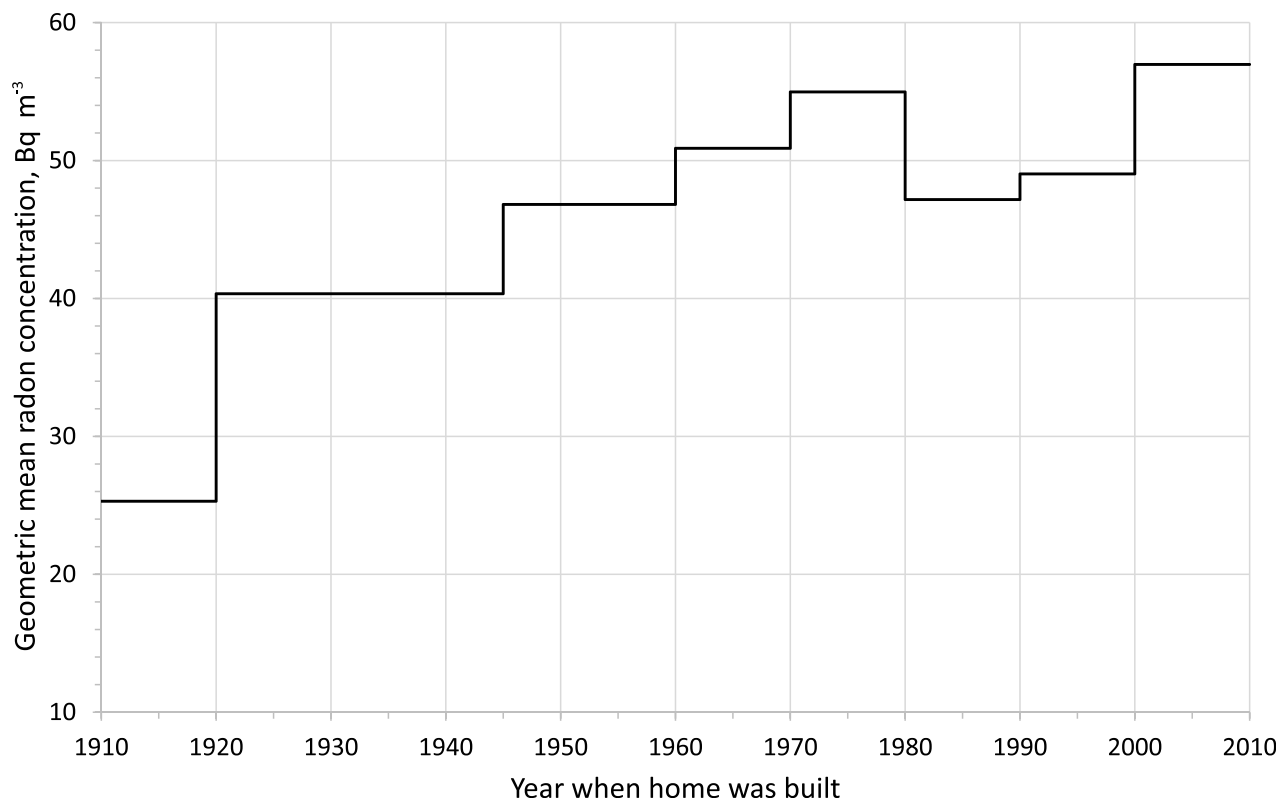
**Fig. 2.** Geometric mean radon concentrations in homes built in different years.

Table 4. Radon distribution characteristics by house type.

House type	N	GM (Bq m ⁻³)	GSD	AM (Bq m ⁻³)
Bungalow	5,382	62	3.11	119
Two-story	4,291	40	3.15	77
Three-story	528	36	3.57	81
Split-level 4-story	1,397	53	3.57	120
Side-by-side	202	30	3.11	57
Duplex	140	24	3.87	61
Townhouse	298	22	3.25	45
Trailer mobile home	494	20	3.18	38
Pre-fabricated home	198	44	3.11	84

radon survey was conducted during the heating seasons. Information collected from the survey can well describe how heating system influences indoor radon level. Table 5 presents radon distribution characteristics by the type of heating. Natural gas is the most popular heating fuel in Canada. Geothermal heating is used in less than 1% of households surveyed. However, households with geothermal heating tend to have higher radon levels, on average, than households with other types of heating. Houses with oil and wood heating tend to have lower radon concentrations.

Material used for heating is not likely to be a source of radon in homes. However, a heating system is likely to influence radon level by affecting indoor air circulation. Most Canadian homes have forced-air central heating systems. Among the three heating systems commonly found in Canadian homes, radon levels tend to be slightly higher in homes with forced air, followed by baseboard heating and radiant heating (see Table 6).

Basement characteristics

The majority of Canadian residences have a full basement underneath the entire house. Some residences have a partial basement or a crawl space. On average, radon levels in houses with a basement are about twice the radon levels in houses without a basement, as shown in the summary statistics in Table 7. By assigning a value of zero to no basement, 0.1 to a crawl space, 0.5 to partial basement, and 1 to full basement, linear regression showed that the observed geometric mean radon concentrations are significantly

Table 5. Radon distribution characteristics by type of heating.

Type of heating	N	GM (Bq m ⁻³)	GSD	AM (Bq m ⁻³)
Natural gas	6,133	52	2.86	90
Electric	4,515	51	3.42	108
Oil	1,757	34	3.95	87
Propane	427	59	2.65	94
Geothermal	120	84	2.81	143
Wood	339	35	3.77	85

Table 6. Radon distribution characteristics by type of heating system.

Heating system in home	N	GM (Bq m ⁻³)	GSD	AM (Bq m ⁻³)
Forced air	9,312	52	3.10	98
Baseboard	2,708	42	3.63	97
Radiant (water)	890	34	3.75	81

correlated with basement types (ANOVA, $F_{1,3} = 25.92$, $R^2 = 0.93$, $p = 0.036$).

In the early cross-Canada radon survey with a single grab sample in summer months (Letourneau et al. 1984; McGregor et al. 1985), it was observed that radon concentrations were higher in homes with the basement windows closed than open. The recent cross-Canada radon survey (Health Canada 2012) also included the presence and operation of basement windows in the questionnaires. Summary results are given in Table 8. Unlike the early survey, the recent survey was conducted during heating season when a majority, if not all, of basement windows are closed. Therefore, the influence of basement windows on indoor radon level cannot be clearly observed.

Water source

Although most Canadian households depend on municipal central distribution systems for their water use, a significant portion (29%) of homes surveyed have private wells. Because radon is extremely volatile and readily released from water into air, houses with private wells tend to have higher radon concentration than houses connected to a municipal water system. While the average GM in houses connected to a municipal central water distribution system is 44 Bq m⁻³ with GSD of 3.17, the average GM in houses using private well water is 60 Bq m⁻³ with a slightly wide GSD of 3.33. On average, the use of private well water could increase indoor radon concentration by 36%, see Table 9.

DISCUSSION

Uranium is a common element found everywhere in Earth's crust. As a result, radon gas can be found in almost all homes in Canada. Concentrations differ greatly across the country, but they are usually higher in areas where there is a higher amount of uranium in underlying rock and soil.

Table 7. Radon distribution characteristics by type of basement.

Type of basement	N	GM (Bq m ⁻³)	GSD	AM (Bq m ⁻³)
Full basement underneath the entire house	9,439	54	3.15	105
Partial basement underneath part of house	1,751	47	3.48	102
A crawl space under all or part of house	1,574	26	3.81	63
No basement, house sits directly on the ground	654	23	3.01	42

Soil radon is the main radon source for Canadian dwellings. Radon can enter a home any place it finds an opening where the house is in contact with the ground: cracks in foundation walls and in floor slabs, construction joints, gaps around service pipes, support posts, window casements, floor drains, sumps, and cavities inside walls. Thus, it was clearly observed in the cross-Canada radon survey that radon concentrations are, on average, significantly higher in homes with a basement.

Uranium, radium, and radon can dissolve in water and, therefore, may enter groundwater supplies that pass through radium-bearing rocks and soils. While water drawn from surface water supplies does not generally contain appreciable levels of radon, high radon concentrations are often observed in groundwater sources (NRC 1999). Private well sources tend to have more radon than public water supplies because they are often drawn from aquifers with low capacity. When these types of aquifers are uranium-bearing granite, metamorphic rocks, or fault zones, the radon concentration in the water tends to be high. Because radon can easily be released from water into air when in use, well water can be an additional source of radon to the indoor environment. The survey results confirmed that radon concentrations are, on average, higher in homes with private well water than homes with municipal water supplies.

Although many environmental factors and housing characteristics can influence the radon level in a home, ventilation rate or air circulation condition is usually the most important modifying factor for the radon concentration. In recent decades, more and more homes have been built to be energy-efficient to reduce heat loss. Newer houses are often more airtight (reduced passive exchange with outdoor air of very low radon concentration) than old houses. This may explain why radon concentrations tend to be higher in newer homes than in older homes if the ventilation systems in newer homes are not appropriately controlled to compensate for reduced air exchange due to increased airtightness.

All of the above analysis on the influence of housing characteristics on indoor radon concentration are at population level and only represent statistical averages. With increased public awareness of radon-induced lung cancer, people often ask questions about the correlation between housing characteristics and indoor radon concentration.

Table 8. Radon distribution characteristics related to the presence and operation of basement windows.

Basement window	N	GM (Bq m ⁻³)	GSD	AM (Bq m ⁻³)
No windows in basement	544	38	4.37	113
Open frequency for windows in basement				
0 to 1 d a year	4,143	59	2.94	105
2 to 30 d a year	4,538	53	3.25	107
31 to 120 d a year	1,650	55	2.89	96
121 or more d a year	416	47	3.22	93

Table 9. Radon distribution characteristics by type of water source.

Water source	N	GM (Bq m ⁻³)	GSD	AM (Bq m ⁻³)
Municipal distribution system	9,363	44	3.17	86
Private well water	3,779	60	3.33	123

However, the fact is that radon concentration levels can vary from one house to another, even if they are similar designs and next door to each other. Therefore, no matter the age, type of construction, or where a home is located, the only way to be sure of the radon level in a home is to test.

CONCLUSION

The first nationwide radon survey in the 1970s established the geographical variation of radon concentrations in Canadian homes. Based on that survey with a single grab sample in roughly 14,000 homes during summer months, radon distribution characteristics were described with the population-weighted arithmetic mean radon concentration of 28.4 Bq m⁻³, geometric mean radon concentration of 11.2 Bq m⁻³, and geometric standard deviation of 3.9. Those characteristics were reported in the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2006 Report to the General Assembly (UNSCEAR 2009). Since the first national survey, especially with the lowering of the Canadian radon guideline for indoor environments from 800 to 200 Bq m⁻³ in June 2007 (Health Canada 2007), there has been a new wave of radon testing with alpha track detectors for at least 90 d and more. Based on those community and nationwide radon surveys in a total of 21,818 homes, radon distribution characteristics in Canada are re-assessed with the population-weighted arithmetic mean radon concentration of 82 Bq m⁻³, geometric mean radon concentration of 55 Bq m⁻³, and geometric standard deviation of 2.45. Based on long-term radon measurements, the new assessment results are more reliable than the results from 1970s. This summary and re-assessment is part of data preparation for the upcoming UNSCEAR Global Survey for public exposure to ionizing radiation (survey.unscear.org).

Acknowledgments—The author would like to acknowledge the members of Health Canada's National Radon Laboratory and contractors, specifically Renato Falcomer, Huixia Jiang, Joseph Kish, Paul Kutyma, Isa Mohammed, Ravi Pooran, Stephen Reid, Rodica Rogojan, Vincent Young, Jeffrey Whyte, and the regional radiation specialists from various Health Canada regional offices for their contribution to the success of the cross-Canada radon survey 2009/2011.

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