A Comparison of Two Methods for Ecologic Classification of Radon Exposure in British Columbia: Residential Observations and the Radon Potential Map of Canada

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ABSTRACT

OBJECTIVE: To compare ecologic classification of radon exposure from observed residential concentrations in BC with classifications based on a map that shows geological radon potential, with particular attention to high-smoking populations.

METHODS: First, residential radon measurements from four health agencies were used to classify 74 local health areas (LHAs) as low, moderate, or high exposure based on the number of homes with concentrations greater than 200 and 600 Bq/m³. Second, the Zone 1 (high), Zone 2 (elevated), and Zone 3 (guarded) risk categories of the radon potential map of Canada were used to make the same exposure classifications based on the population-weighted area of each zone in each LHA. Agreement was compared and quantified. Average smoking rates in each LHA were used to further assess agreement for smokers, who are a high-risk group.

RESULTS: Both methods showed a range of exposure across LHAs. The radon potential map classified more areas as high exposure than the observed radon concentrations, and the methods agreed in 30 of 74 LHAs. The radon potential map identified much of the southern coastal region as high exposure, but 617 of the 621 observed concentrations were ≤ 200 Bq/m³, and no observations were >600 Bq/m³. An estimated 36% of the BC population and 35% of BC smokers live in the southern coastal region.

CONCLUSIONS: The radon potential map of Canada may communicate potential radon risk, but it was not designed for epidemiologic exposure assessment. Overall, the potential map classified 34 LHAs as higher than observed, and 10 LHAs as lower than observed. The potential map should only be used to inform exposure assessment in conjunction with observed radon concentrations.

KEY WORDS: Radon; environmental exposure; epidemiologic methods; geographic information systems; risk assessment

La traduction du résumé se trouve à la fin de l'article.

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Radon is a colourless, odourless, naturally-occurring radioactive gas produced by the decay of uranium in soil and rocks. Ambient concentrations of radon are typically low, but it can infiltrate homes and other buildings through cracks in the foundation and floors, and can accumulate to high indoor concentrations, particularly during the winter. Exposure to radon gas is the second-leading cause of lung cancer (behind tobacco), and the leading cause in non-smokers.¹ Several case-control studies report an 8-12% increase in lifetime risk of lung cancer associated with each 100 Becquerel per cubic metre (Bq/m³) increase in long-term exposure to radon,²⁻⁴ and no evidence of a threshold or "safe" level of exposure.² Smoking and radon also interact synergistically, causing a greater increase in lung cancer risk for smokers than for non-smokers.⁵ Overall, radon-induced lung cancer is estimated to account for more than 3,000 deaths in Canada and more than 200 deaths in British Columbia (BC) every year, of which approximately 85% occur in smokers.⁶

To date there has been a single epidemiologic study on residential radon exposure in Canada.⁷ A case-control analysis of 738 lung cancers found no significant association between radon exposure and histologic cancer types after adjusting for smoking and educational status. Similar studies from other countries have reported similar results, therefore much of the evidence for residential radon

policy in Canada and worldwide has been derived from meta-analyses that increase statistical power by combining data from multiple case-control studies.²⁻⁴ Ecologic designs provide another way to increase the size of study populations. To date there have been no ecologic studies on radon exposure in Canada, but those conducted elsewhere report associations between radon and multiple cancers.⁸⁻¹⁰ Although ecologic studies are imperfect,⁸ it has been argued that they have some advantages over alternate designs, particularly when "the geographic basis for differences in exposure may be more accurately identified and free of bias than the individual determinants within geographic areas".¹¹ Such is the case with radon, where differences between geographic areas are clear and objective, but assessment of differences between individuals within the same geographic area would require subjective recall and retro-

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spective measurement of all residences, schools, and workplaces. In addition, ecologic studies are inexpensive to conduct, and can often take advantage of large administrative databases. Therefore, it is possible that ecologic studies could play an important role in advancing radon research and policy in Canada, provided that exposure can be appropriately assessed. The following work compares two possible methods for ecologic exposure classification based on 1) observed residential concentrations and 2) the radon potential map of Canada. Agreement between the methods is evaluated for all BC residents and for current smokers, who are at highest risk of radon-induced lung cancer.

Residential radon concentrations are typically measured using long-term detectors. Health Canada recommends sampling for at least 90 days during the heating period to ensure a representative result. In BC, several radon measurement campaigns have been conducted by universities, regional and provincial governments, and non-governmental organizations over the past 20 years. Although these data were not collected for exposure assessment purposes, they show clear variability in the provincial distribution of radon concentrations.¹²

In 2011, the Radon Environmental Management Corporation created a radon potential map of Canada to indicate areas where natural environmental conditions might produce high ambient radon concentrations.¹³ Three sources of information were used to estimate the radon potential of each geologic unit (an area of rock defined by distinctive features), under the hypothesis that radon risk is proportional to the uranium present in underlying rocks and soil: 1) results from multiple geochemical surveys that measured the composition of 388,855 stream and 174,881 lake bottom sediments to identify the underlying uranium content; 2) results from multiple geophysical surveys that measured the naturally-occurring radiation; and 3) geologic potential categories extrapolated from the 1993 radon potential map of the United States produced by the US Geological Survey.¹³ These three sources were weighted to give preference to directly measured data (geochemical and geophysical surveys), and the results were summed to generate a national map of radon risk. The map divides Canada into three approximately equal-area classes based on relative radon hazard: Zone 1 (high) has geologic conditions that may lead to higher radon concentrations than Zone 2 (elevated) or Zone 3 (guarded).

METHODS

Radon observations

We had a total of 3,867 residential radon observations from four sources. The BC Centre for Disease Control (BCCDC) tested 1,449 homes from 1991-1992. This survey was designed to represent populations living in areas with low, moderate, and high background radiation, with oversampling in the areas of highest expected concentrations.¹² The Northern Health Authority collected volunteer samples from 339 homes in northern BC from 1997-2001 and 2009-2012. Similarly, the BC Lung Association collected volunteer samples from 263 homes throughout BC from 2010-2012. Finally, from 2010-2012, as part of its cross-country survey, Health Canada tested 1,817 homes across BC designed to be statistically representative of 121 geographic health areas, including the 16 health service delivery areas in BC.¹⁴ It is possible but unlikely that a single residence was sampled in more than one survey. Each of the four

Figure 1. Location of communities with residential radon observations

Different circles represent the number of observations in the following categories: <20, 20-49, 50-99, and ≥100. Lines indicate the borders of 83 local health areas (LHAs).

datasets included different levels of detail about the residences sampled, but all had two variables in common: the community in which the residence was located, and the radon concentration. We extracted these variables from all four datasets, and mapped the 268 communities in a geographic information system (GIS) using a BCCDC file that gives the central latitude and longitude of all communities in BC (Figure 1).

The Local Health Area (LHA) is the smallest unit of health geography in BC, and we assigned each community and all of its observations to one of 83 LHAs. Although there are 89 LHAs in total, we collapsed the sub-areas comprising the municipalities of Vancouver and Surrey because each was represented by a single latitude and longitude coordinate in the BCCDC communities file. Of the 83 LHAs, 80 (96.4%) had at least one observation, and 47 (56.6%) had at least 20 observations. Health Canada recommends remediation for homes with radon concentrations greater than 200 Bq/m³ and immediate action for homes with concentrations greater than 600 Bq/m³.¹⁵ Thus, we classified the LHAs into low, moderate, and high exposure categories as follows:

- LHAs with ≥20 observations were classified as high exposure if ≥5% of the measurements were >600 Bq/m³, as moderate exposure if ≥5% of the measurements were >200 Bq/m³, and as low exposure otherwise.
- LHAs with <20 observations were classified as high exposure if they had any observations >200 Bq/m³, and as low exposure if all observations were ≤200 Bq/m³ and the LHA was adjacent to at least one of the low exposure LHAs identified above.

There were six LHAs that had fewer than 20 observations (all ≤200 Bq/m³) but were not adjacent to other low exposure LHAs. These remained unclassified, along with the LHAs that had no radon observations, leaving a total of nine unclassified LHAs.

Figure 2. Radon exposure classifications based on observed data (A) and the radon potential map of Canada (B)

Radon potential

The radon potential map of Canada classifies the radon risk in each geological unit as Zone 1 (high), Zone 2 (elevated), or Zone 3 (guarded). To classify the corresponding radon exposure in each LHA, we divided BC into the 7,849 dissemination areas (DAs) from the 2001 census, and assigned each one to an LHA using its geographic centroid. Next, we overlaid the radon potential map with DA polygons in a GIS, and calculated the percent of each risk zone in each DA area. Finally, we calculated the population-weighted average of the risk zones in each LHA, and assigned LHA exposure categories based on the risk zone that covered the largest population. For example, an LHA with 33%, 32% and 35% of its population in Zone 1, Zone 2, and Zone 3, respectively, was classified as low exposure. However, only 5 of the 74 LHAs were classified using less than the majority of the population (with proportions ranging from 43% to 48%).

Population and smoking data

The 2001 population of each LHA was downloaded from BC Stats¹⁶ to reflect provincial demographics in a census year that was central to the date range for the radon observations. Smoking estimates were obtained from the 2008-2009 Canadian Community Health Survey (CCHS). The CCHS generally samples to be statistically representative of the 16 health service delivery areas in BC, but the BC Ministry of Health contracted Statistics Canada for oversampling in the 2008-2009 cycle to produce estimates that were statistically representative at the LHA level.^{17,18} Even so, 21 of the LHAs with smaller populations had to be aggregated into 10 larger units to allow for stable estimates. We received data on the percent of current smokers living in each LHA (or group of LHAs) from the BC Ministry of Health.

Comparisons

After classifying the exposure in each LHA using both the observed radon concentrations and the radon potential map, we overlaid the

results to assess where the classifications agreed and disagreed. Agreement between the methods was described using a 3x3 table, and the following five categories:

- Agreement: both methods give same classification.
- Potential 2 Categories Higher: radon potential classification two levels higher than observed classification (i.e., radon potential exposure was high and observed exposure was low).
- Potential 1 Category Higher: radon potential classification one level higher than observed classification (i.e., radon potential exposure was high and observed exposure was moderate, or radon potential exposure was moderate and observed exposure was low).
- Potential 1 Category Lower: radon potential classification one level lower than observed (i.e., radon potential exposure was moderate and observed exposure was high, or radon potential exposure was low and observed exposure was moderate).
- Potential 2 Categories Lower: radon potential classification two levels lower than observed classification (i.e., radon potential exposure was low and observed exposure was high).

As a secondary analysis, we restricted the radon observations to the dataset collected by Health Canada, because it had the most representative sampling strategy and because these data should be available by community to all provinces upon request. All analyses were performed using R¹⁹ and ArcGIS 10.

RESULTS

Radon observations were used to classify exposure in 74 of 83 LHAs, which included 98.7% of the BC population (Figure 2a, Table 1). Of these, 43 were classified as low exposure (76.7% of the population), 16 were classified as moderate exposure (16.6% of the population), and 15 were classified as high exposure (5.4% of the population). The high and moderate exposure LHAs also had higher smoking rates than the low exposure LHAs (21.6% and 20.8%, respectively, compared with 16.3%). The high exposure LHAs were most com-

Table 1. Comparison of Exposure Classifications for 74 of 83 Local Health Areas (LHAs) in British Columbia, According to Radon Observations From All Data Sources and the Radon Potential Map of Canada

	LHAs	BC Population	Current Smokers
Radon observations			
Low	43	76.7%	16.3%
Moderate	16	16.6%	20.8%
High	15	5.4%	21.6%
Radon potential			
Low	27	48.7%	16.6%
Moderate	11	8.9%	18.0%
High	36	41.1%	18.0%
Difference			
Agree	30	40.9%	15.9%
Potential 2 categories higher	17	30.5%	16.9%
Potential 1 category higher	17	16.5%	19.6%
Potential 1 category lower	6	8.0%	20.2%
Potential 2 categories lower	4	2.9%	21.5%
No data	9	1.3%	20.5%

Table 2. The 3x3 Table of Observed and Potential Radon Categories

		Radon Observations		
		Low	Moderate	High
Radon potential	Low	19 _d	4 _c	4 _c
	Moderate	7 _b	2 _a	2 _c
	High	17 _b	10 ^a	9 ^a

To estimate the sensitivity and specificity, the subscripts a, b, c, and d correspond with true positives, false positives, false negatives, and true negatives, respectively, as suggested by Canivez (1996).²³ Values with no subscripts are not considered in the calculation.

mon in the interior regions, and the largest concentration of low exposure LHAs occurred around the southern coastal region (Figure 2a).

The radon potential map was used to classify exposure in the same 74 LHAs (Figure 2b, Table 1). In this case, 43 were classified as low exposure (48.7% of the population), 11 were classified as moderate exposure (8.9% of the population), and 36 were classified as high exposure (41.1% of the population). The high and moderate exposure LHAs had slightly higher smoking rates than the low exposure LHAs (18.0% compared with 16.6%). The high exposure areas dominated the Kootenay, Okanagan, coastal, and Vancouver Island regions, while low exposure areas were more common in the northern interior (Figure 2b).

Agreement between the two methods varied across the province (Figure 3). Both methods produced the same classification in 30 of the 74 LHAs (40.9% of the population), 19 of which were low, 2 were moderate, and 9 were high. The radon potential map produced higher classifications than the radon observations in 34 LHAs (47.0% of the population) and lower classifications in the remaining 10 LHAs (10.9% of the population). Using the 3x3 table (Table 2), the estimated sensitivity of the radon potential map compared with the radon observations was 0.58, with a specificity of 0.44. The positive and negative predictive values were 31% and 70%, respectively. The LHAs with different observed and potential radon classification had more smokers than the LHAs where both methods agreed; the highest percentage of smokers was found in the four LHAs where the observed classification was two categories higher than the radon potential classification (Table 1).

When analyses based on radon observations were restricted to data from the national Health Canada survey, 47 of 74 LHAs were classified as low exposure (82.0% of the population), 11 were classified as moderate exposure (12.2% of the population), and 16 were

Figure 3. Exposure classifications based on the radon potential map of Canada compared with classifications based on residential radon observations

classified as high exposure (4.6% of the population). When these classifications were compared with the radon potential map, 33 LHAs (44.8% of the population) were assigned to the same exposure categories, of which 20 were low, 1 was moderate, and 12 were high. The radon potential map produced higher classifications than the radon observations in 32 LHAs (45.2% of the population) and lower classifications in the remaining 9 LHAs (8.9% of the population). Smoking rates followed a similar pattern to the results using data from all sources.

DISCUSSION

Comparing ecologic exposure classification based on 1) residential radon observations and 2) the radon potential map of Canada yielded distinct areas of agreement and disagreement. Relative to the observed concentrations, the potential map underestimated indoor radon exposure in parts of the BC interior, including the populous Prince George LHA, and overestimated exposure around the southern coast and Vancouver Island (Figure 3). While both methods agreed for many LHAs, the radon potential map was more likely to overestimate the exposure than to classify it consistently with the radon observations. As such, the radon potential map indicated a much larger percentage of the BC population to be highly exposed than the observed radon observations (41.1% compared with 5.4%). This is partially due to fundamental differences in the distributions of the underlying data. The radon observations were log-normally distributed, suggesting that a small fraction of the population is exposed to very high concentrations. On the other hand, the zones of the radon potential map are equally distributed over the Canadian land mass, suggesting that 33% of the population would be in Zone 1 (high) if the population was also equally distributed. Results might have been different had the radon poten-

tial zones been equally distributed over the land mass of British Columbia (the current provincial area distribution is 36.1% high, 23.4% moderate, and 40.5% low).

Differences between the observed and potential radon data required us to make important decisions about exposure classification for both methods. For the radon observations, we assumed that the available samples were representative of the exposure within the LHA population, and we selected the 5% cut-off based on the relative distribution of concentrations across the LHAs. For the radon potential map, we explored multiple definitions based on percentages of the populations in each zone, but these produced too little variability between LHAs to develop a meaningful comparison between methods. Indeed, we tested several classification schemes for both data types, and the methods presented here produced the greatest agreement between them. Increasing or decreasing thresholds for the radon observations and/or radon potential would simply decrease or increase the number of LHAs classified as high or low exposure, respectively. However, different thresholds would not have changed the relative distribution of the areas where the methods disagree.

Further discrepancy between radon observations and radon potential can be attributed to non-geologic factors that are known to affect indoor concentrations. A large study in England found that indoor radon was influenced by the type and ownership of the house, its age, and the presence or absence of double-glazing and draft-proofing.²⁰ These latter characteristics are more common in the cold BC interior than in the temperate coastal areas, which were the areas of most disagreement between the classification methods. In England, however, these factors combined to explain only 9% of the total variation in measured radon, whereas the radon potential of the geological unit was the strongest single predictor, accounting for only 20% of the variation.²⁰

The finding that high radon potential does not necessarily translate to high residential radon concentrations is not unique. An Italian map of four radon potential categories (low, medium, high, and very high) was compared with 1,427 residential radon observations divided into five concentration categories (<100, 100-200, 200-400, 400-1000, and >1000 Bq/m³). Some of the homes in each concentration category were located in very high radon potential areas, but none of the homes in the highest concentration category were located in low radon potential areas.²¹ In Northern Ireland, a well-established risk communication map based on observed concentrations was compared with a newly developed radon potential map based on bedrock geology. Considerable differences were found between the two, and high radon was consistently observed under geologic conditions that were defined as having low radon potential.²²

The BCCDC is fortunate to have access to such a rich database of provincial radon observations, but all provinces can request access to results from the cross-country survey conducted by Health Canada. When we restricted our analyses to these 1,817 observations, the overall results were similar, but a larger proportion of the total BC population was classified as low exposure when compared with the complete observation dataset. This was primarily because the Health Canada survey was designed to be representative of the entire population, so had fewer observations of concentrations greater than 200 Bq/m³ in two relatively populous LHAs, causing their classifications to shift from moderate exposure to low expo-

sure. In contrast, the BCCDC oversampled in high-radon areas in order to better characterize high-risk zones.

The radon potential map of Canada was designed to communicate about radon risk, especially for areas with little observed data. From this perspective, it may be useful that the map suggests more ambient radon in BC than the indoor observations show. The only way to know the radon concentration in a specific building is to test, and it is preferable for people to test and find low radon exposures than for people with high radon exposures not to test. Furthermore, geologic potential remains the strongest predictor of indoor radon concentrations in the absence of radon observations,²⁰ and much of Canada remains unmeasured.

The radon potential map of Canada was not designed for use in epidemiologic research, and further work is needed to examine the conditions under which its estimates are strongly and weakly associated with observed radon concentrations. When compared with exposure classifications based on radon observations, we found that radon potential classifications agreed in 40.5% of geographic areas, overestimated exposures in 45.9% of areas, and underestimated exposures in 13.5% of areas. Furthermore, smoking prevalence was highest in the underestimated areas. This is an area for particular caution, because smokers are at much higher risk of radon-induced lung cancer. At this time, we recommend that the radon potential map should only be considered for epidemiologic research in conjunction with adequate observed data to qualitatively assess the exposure classification scheme. Our analyses suggest that an ecologic study on lung cancer and radon exposure in BC might reach divergent conclusions depending on whether the radon potential map or the radon observations were used for exposure assessment.

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RÉSUMÉ

OBJECTIF : Comparer la classification écologique de l'exposition au radon selon 1) les concentrations dans les habitations observées en Colombie-Britannique et 2) les classifications basées sur une carte montrant le potentiel géologique d'exhalation de radon, en accordant une attention particulière aux populations où le tabagisme est élevé.

MÉTHODE : Premièrement, nous avons utilisé les mesures du radon dans les habitations provenant de quatre organismes de santé pour classer 74 circonscriptions sanitaires (CS) selon leur niveau d'exposition (faible, modéré ou élevé) d'après le nombre d'habitations ayant des concentrations supérieures à 200 et à 600 Bq/m³. Deuxièmement, les catégories de risque selon la carte du potentiel en radon du Canada (Zone 1 [niveau le plus élevé], Zone 2 [niveau élevé] et Zone 3 [prudence]) ont servi à établir les mêmes classifications de l'exposition d'après la superficie pondérée de chaque zone, dans chaque CS. Les données concordantes ont été comparées et chiffrées. Ensuite, les taux de tabagisme moyens dans chaque CS ont servi à évaluer la concordance des données pour les fumeurs, qui constituent un groupe à risque élevé.

RÉSULTATS : Les deux méthodes montrent divers niveaux d'exposition d'une CS à l'autre. La carte du potentiel en radon classe davantage de zones dans la catégorie de niveau le plus élevé que les concentrations observées, et les deux méthodes concordent pour 30 des 74 CS. Selon la carte du potentiel en radon, une grande partie de la région côtière sud affiche le niveau d'exposition le plus élevé, mais 617 des 621 concentrations observées sont < 200 Bq/m³, et l'on n'a observé aucune concentration > 600 Bq/m³. Selon les estimations, 36 % de la population britanno-colombienne et 35 % des fumeurs de la Colombie-Britannique vivent dans la région côtière sud.

CONCLUSIONS : La carte du potentiel en radon du Canada peut communiquer le potentiel d'exposition au radon, mais elle n'est pas conçue pour l'évaluation du risque épidémiologique. Globalement, la carte du potentiel classe 34 CS dans une catégorie supérieure au niveau observé et 10 CS dans une catégorie inférieure au niveau observé. Cette carte ne devrait donc être utilisée que pour éclairer l'évaluation de l'exposition, conjointement avec les concentrations en radon observées.

MOTS CLÉS : radon; exposition environnementale; méthodes épidémiologiques; systèmes d'information géographique; évaluation du risque