BC Centre for Disease Control
An agency of the Provincial Health Services Authority

Radon in Household Well Water: Contributions to Indoor Air Radon Concentrations

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Introduction

The Environmental Health Services at the BC Centre for Disease Control was requested by an Interior Medical Health Officer to provide information on the contribution of waterborne radon to indoor air levels of radon in homes, as well as the potential to use radium & uranium concentrations as an indicator of radon levels in tap water. Through off-gassing, radon in tap water can be released to indoor air in homes.

In response to this inquiry, EHS/BCCDC conducted a review of national and international drinking water guidelines and standards for radium and radon to provide an overview of current health-protective reference levels. Modelling was conducted to estimate the average incremental concentration contributed by water to air, taking into account parameters such as radon concentrations in water, water usage, and air exchange in a home.

In this report, we provide a brief background on uranium, radium and radon, a review of drinking water guidelines and standards, and the methods, results, and discussion of the radon modelling exercise.

Uranium, Radium and Radon in the Environment

Radium (^{226}Ra) and radon (^{222}Rn) are released to the environment through the decay of uranium (^{238}U), as shown in Figure 1. Uranium can be present in bedrock, where it can dissolve to also enter surrounding soil and water. The decay of uranium results in the formation of ^{226}Ra, which then decays to form ^{222}Rn. Ultimately, ^{222}Rn will decay to form lead (^{206}Pb), a stable element.

^{226}Ra (referred to here as radium, unless otherwise specified) is present in the environment as a heavy element. In contrast, ^{222}Rn (referred to here as radon, unless otherwise specified) is a gas which can easily move between media, including bedrock, soil, and water. The solubility of radon in water is low and therefore, it can easily escape from water to air. For this reason, surface waters generally do not contain appreciable amounts of radon. In municipally treated groundwater, radon concentrations are reduced through treatment processes which expose water to air. Groundwater obtained from private wells generally has the highest radon concentrations because this water is less exposed to air before reaching households. Radon enters groundwater via two main pathways: 1) through decay of radium present in water, or 2) through movement of radon from surrounding soil or bedrock. To a lesser degree, additional radon can be generated in household water through decay of radium deposits along household plumbing.[1]

In homes, activities that involve the agitation or heating of water can liberate radon present in water to air. Showering, washing dishes, and laundering can release waterborne radon to air; to a lesser degree, the use of toilets and dishwashers can also release of radon from water to air.

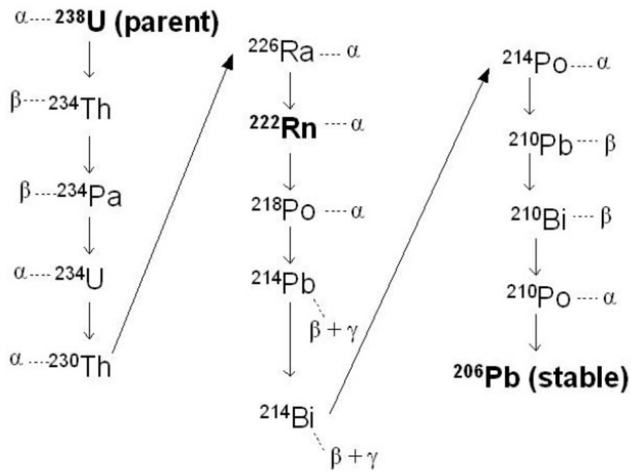

Figure 1: Uranium-238 decay chain[2]

Health and Exposure

Although uranium is a radioactive element, its health effects (primarily kidney damage), are due to its chemistry. In contrast, health impacts of radium and radon exposure are primarily radiological. Both radium and radon emit radiation in the form of alpha particles; once ingested or inhaled, they can cause damage to bodily tissues and organs. Because alpha particles are heavy and short-ranged, they cannot penetrate physical barriers, including clothing and skin.

Ingestion is the primary route of exposure to radium in water. Once ingested, radium can be absorbed into the blood system and deposited into bones. Studies of occupationally exposed individuals show that long-term exposures to ingested radium can lead to depression of the immune system, anemia, cataracts, fractured teeth, as well as increased risk of bone cancer.[3]

Individuals can be exposed to radon in water via inhalation and ingestion, although the primary route of exposure is considered to be inhalation. There is a well established link between lung cancer and inhalation of radon; ingestion of radon has been weakly linked to stomach cancer. The estimated risks of these health outcomes differ by several orders of magnitude: risk of stomach cancer over a lifetime of radon exposure at 1 Bq/m^3 is estimated to be 1.9×10^{-9} while risk of lung cancer is 1.3×10^{-4}.[4] For this reason, public health programs on radon have been focused primarily on raising awareness and encouraging testing and mitigation of airborne exposures to radon (due to soil gas intrusion) in homes.

Testing Radon in Water

The concentration of radon in water can be determined using one of three analysis methods: liquid scintillation, gas extraction, or direct gamma counting. Of these, liquid scintillation is considered to be the most accurate method, with detection limits close to 1 Bq/L for a sample size of 40 mL.[5] Samples are typically collected at the tap, after running water for 2-3 minutes to remove stagnant water lying in household plumbing, and sent to a laboratory for analysis.

Drinking Water Guidelines and Standards

The Canadian drinking water guideline for radium (^{226}Ra) is 0.5 Bq/L. In comparison, the World Health Organization's guidance level is 1 Bq/L while the U.S. Environmental Protection Agency's standard is set at 5 pCi/L (approximately 0.2 Bq/L).

No drinking water guidelines or standards for radon (^{222}Rn) in drinking water have been developed by Health Canada, the World Health Organization (WHO) or the U.S. Environmental Protection Agency (US EPA). While it is not deemed necessary in Canada due to typically low levels,[6] the WHO does provide some guidance, suggesting that remediation is necessary at concentrations above 1,000 Bq/L of radon in water. In 1999, the US EPA proposed a Maximum Contaminant Level (MCL) as well as an Alternative MCL (AMCL) of 300 pCi/L (11 Bq/L) and 4000 pCi/L (148 Bq/L), respectively; these values have not yet been finalized. The MCL and the AMCL are intended to reflect two approaches to radon risk reduction, one which targets water as an important source and one which takes a multi-media approach, targeting soil gas intrusion. Although no radon standard exists at the U.S. federal level, state-level drinking water standards or guidelines have been developed, including the states of Connecticut (185 Bq/L), Maine (148 Bq/L), and Massachusetts (370 Bq/L). Finally, the European Union has provided its member states with some guidance on developing reference levels for radon in water, suggesting that below 100 Bq/L no action be taken and above 1000 Bq/L remediation should take place.

Table 1 summarizes guidelines, standards, and reference values developed by Health Canada, U.S. EPA, some U.S. States, WHO, and the European Union.

Table 1 Summary of Guidelines, Standards, and Action Limits for Radium (^{226}Ra) and Radon (^{222}Rn) in Drinking Water

Agency	Type of guideline/ standard/limit	Contaminant	Value	Health endpoint	Comments
Health Canada (2010)[6]	Maximum Acceptable Concentration (MAC) Guideline	^{226}Ra	0.5 Bq/L	Cancer (not specified)	MAC based on reference dose of 0.1 mSv/year, consumption rate of 730 L/year, and dose coefficient of 2.2 x 10^{-7} Sv/Bq (see Appendix) Assumes ~ 20% of ingested radium is absorbed by the gastrointestinal tract
		^{222}Rn	---	---	Not deemed necessary
World Health Organization (2008)[7]	Guidance level (GL)	^{226}Ra	1 Bq/L	Cancer (not specified)	GL based on dose coefficient of 2.8 x 10^{-4}, water consumption of 730L/year
		^{222}Rn	None	N/A	Recommend that controls should be implemented if radon levels exceed 100 Bq/L
U.S. Environmental Protection Agency (2009)[8,9]	Maximum Contaminant Level (MCL) Standard	^{226}Ra and ^{228}Ra (combined)	5 pCi/L (0.19 Bq/L)	Cancer (not specified)	EPA also has an MCL of 15 pCi/L for gross alpha emitters
	Proposed Regulation (since 1999) for a Maximum Contaminant Level (MCL) & alternative MCL (AMCL)	^{222}Rn	MCL: 300 pCi/L (11 Bq/L) AMCL: 4000 pCi/L (148 Bq/L)	Lung cancer (via inhalation)	Proposed regulations allow individual states to chose between two options: (1) Adopt a health-based MCL of 300 pCi/L or, (2) Adopt a higher AMCL of 4000 pCi/L in combination with a multi-media mitigation program aimed to address health risks of indoor air
Maine Department of Health and Human Services (2006)[10]	Proposed Maximum Exposure Guideline (MEG)	^{222}Rn	4000 pCi/L (148 Bq/L)	Lung cancer (via inhalation)	MEG is not intended to trigger immediate action (i.e., remediation), but to suggest the need for follow-up testing.

Connecticut Department of Public Health (2011)[11]	Guidance Level (GL)	^{222}Rn	5000 pCi/L (185 Bq/L)	Lung cancer (via inhalation)	Recommend that remediation be conducted if average of two tests is ≥ GL. Tests should be conducted 3 months apart.
Massachusetts Department of Environmental Protection (2007)[12,13]	Standard	^{222}Rn	10,000 pCi/L (370 Bq/L)	Lung cancer (via inhalation)	The standard serves as an "action limit"; should trigger indoor air radon testing.
Vermont Department of Health (2005)[14]	Standard	Alpha radiation	15 pCi/L (0.56 Bq/L)	Bone cancer (for radium exposure); Kidney damage (for Uranium exposure)	Exceedance of US EPA standard signals a need to conduct follow up testing. Specifically, "if the gross alpha result is greater than15 pCi/L, test for Radium-226, Radium-228 and Uranium."
European Union (2001)[15]	Proposed reference levels	^{222}Rn	100 Bq/L or higher (to be set by member states) 1000 Bq/L should trigger remediation	Lung cancer (via inhalation)	No remedial action should be required < 100 Bq/L. Member states should set a reference level (action level) for radon. A level > 100 Bq/L can be set if national surveys show that a higher level is needed to practically implement a radon program. For individual water supplies (excluding commercial or public activity), remedial action should be taken if levels ≥ 1000 Bq/L

Modeling Radon Concentrations in Air

The contribution of radon in water to indoor air depends on several factors: concentration of radon in water entering homes, amount of water used, how water is used, as well as characteristics of the home. Table 2 summarizes some of the main factors that impact the release of radon from water to air and airborne radon levels in homes.

Table 2 Summary of factors influencing the contribution of Radon in water to airborne levels

Factor	Description
Concentration of radon in water	Three sources contribute to the presence of radon in water entering a home: 1. Radon can form through the decay of radium present in water. 2. Radon can enter water that is in contact with radium-containing bedrock or soil. 3. Radon can enter household water through decay of radium deposits in household plumbing.
Water usage	The amount of water used in a household, as well as the specific activity, influence its release. Activities which heat and/or agitate water release more radon from water.
Housing characteristics	The concentration of radon in the air will be influenced by the air exchange rate in the home, as well as the volume of the home.

The National Academy of Sciences (NAS) has published two extensive reviews on the public health risks of radon in drinking water.[16] In their most recent report, BEIR VI, NAS summarize findings from studies investigating the transfer of radon from water to air. This report discusses the use of a model (Equation 1) derived by Nazaroff et al. (1987)[17] to estimate the average incremental concentration that radon in water contributes to air, taking into account the parameters listed in Table 2.

$$Ca = \frac{C_w \, W \, e}{V \, \lambda} \qquad \text{(Equation 1)}$$

Where:

C_a = the average incremental increase of radon in air (Bq/m^3)

C_w = the radon concentration in water entering the dwelling (Bq/m^3)

W = the water-use rate per resident (m^3/person/hr)

e = the use-weighted average transfer efficiency of radon to air (dimensionless)

V = the volume per resident of the dwelling (m^3/person)

λ = the air-exchange rate of the dwelling (hr^{-1}); ventilation in the home is assumed to decrease radon levels much faster than the physical decay of radon in air (0.0076 hr^{-1})

The water-use, transfer efficiency, volume, and air exchange parameters can be replaced with a single transfer factor parameter (f) in a simplified model (Equation 2):

$$C_a = f\, C_W \qquad \text{(Equation 2)}$$

Where: $f = \frac{W e}{V \lambda}$ (dimensionless transfer factor)

The value of the transfer factor (f) can be determined experimentally or estimated using mathematical models. Few studies have evaluated *f* through experimentation. To calculate the value of *f*, these studies generally measure the concentration of radon in air and water in a home, using one of two approaches. The first approach is to take continuous measurements of radon in the air for several days and calculate the difference in average concentrations between time periods in the home, when water is used and when water is not used (e.g., daytime versus nighttime). The difference in concentrations between the two periods is considered to be the contribution of waterborne radon to indoor air concentrations. The second approach is to take continuous measurements of radon in air in a home and identify peaks in concentrations. Peak periods, which directly correspond to periods of water usage (including showering or dishwashing), are then attributed to waterborne radon being liberated to air. There are problems with both study designs; mainly, the uncertainty around radon measurements collected over very short time periods. Due to the short sampling periods and small sample sizes (i.e., number of homes tested), the results from such experimental studies have largely not been generalizable.

Apart from the experimental approach, mathematical models can also be used to understand the contribution of radon in water to air. Specifically, the distribution of the transfer factor (f) can be estimated by modeling the relationship between water usage (W), transfer efficiency (e), volume (V), and air exchange (λ). Average values or distributions of each of these terms can be used. Nazaroff et al. 1987 review studies which use different values for W, e, v, and λ to estimate *f*, and report that most studies consistently find *f* to be close to 1.0×10^{-4}. Similarly, in their BEIR VI report, NAS summarize research findings of modeled values of *f*. Based on their review, the committee recommends that a value of 1.0×10^{-4} be used as the best estimate of *f*.[16] Although a specific uncertainty of the central estimate (1.0×10^{-4}) is not provided, the committee states that the central limit is assumed to have the highest likelihood of lying within a range of $0.8\text{-}1.2 \times 10^{-4}$.

Methods

We estimated the contribution of radon from water to air in a residence using a model developed by Nazaroff et al. 1987 (equation 2).[17] The upper, lower, and central estimates of the transfer factor, f, cited in the BEIR VI report were used.[16]

We were not able to find any useful data on radon concentrations in Canadian well waters. For this reason, we used two of the highest values reported by US EPA surveys (as reported by Nazaroff et al. 1987[17]). These were 65,600 Bq/m^3 (Rhode Island) and 37,400 Bq/m^3 (Maine).[17] Additionally, we also used the US EPA's proposed action level of 148,000 Bq/m^3 (4,000 pCi/L).

Results

We estimated that radon in water, at concentrations of 37,400, 65,600, and 148,000 Bq/m^3, contribute average incremental concentrations of 4, 5, and 15 Bq/m^3 to indoor air concentrations of radon, at a transfer factor of 1.0 x 10^{-4}. Table 3 summarizes the average incremental concentrations predicted for the upper and lower estimates of the transfer factor.

Table 3 Estimates of the average incremental concentration of radon in air (C_a) from radon in water (C_w) based on three transfer factors (f)

	C_a (Bq/m^3)		
C_w (Bq/m^3)	f= 0.8 x 10^{-4}	f= 1.0 x 10^{-4}	f=1.2 x 10^{-4}
37,400	3	4	4
65,600	5	7	8
148,000	12	15	18

Discussion

We estimated the average incremental concentration contributed to air by waterborne radon in a household. Using two of the higher values from a U.S. sampling survey, we estimated that waterborne radon contributed less than 10 Bq/m^3 to indoor radon levels; this is a minor contribution when considering the Health Canada guideline for indoor radon concentrations is 200 Bq/m^3. Similar results were found using an action level proposed by the US EPA, where radon in water is expected to contribute less than 20 Bq/m^3 to indoor air levels. Based on these numbers, we expect that water contributes minimally to indoor air levels of radon in a home.

Several pieces of information are needed to put these numbers into context. First, these estimations are based on a model developed by Nazaroff et al. (1987)[17] which assumes complete mixing of air in the dwelling. Estimates are provided for the average incremental contribution of waterborne radon to air in the entire home; in reality, higher concentrations would be expected in rooms where water use is higher, including the bathroom and kitchen, especially if the air exchange in these rooms is limited. The value of the transfer factor used in this model heavily influences the estimate of radon released from water to air. Most studies have reported that the transfer factor is in the range 0.8 10^{-4} to 1.2 x 10^{-4}, the upper and lower limits of which were included in our estimates. Many factors will influence the transfer of radon from air to water, including the temperature and volume of water used, and the volume and air exchange rate in a home. Higher concentrations would be expected in winter when air exchanges rates are lower, in comparison to the summer season.

The estimates provided here do not address the absolute impact of the contribution of waterborne radon in homes where soil gas intrusion results in elevated airborne concentrations of radon. In radon-prone homes, even a small incremental increase in radon concentrations could have a non-negligible impact.

We found no data on radon levels in Canadian groundwater supplies. Measurements of radon concentrations in tap water samples, collected from homes using private wells, would allow for a better assessment and understanding of the contribution of waterborne radon to levels in air, in Canadian homes.

Summary

Several jurisdictions have developed guidelines or standards for radon and radium levels in drinking water. Health Canada has not developed a drinking water guideline for radon, stating that it is not deemed necessary, due to the low levels of radon in Canadian waters. While surface waters and municipally treated groundwater generally have low concentrations of radon, high concentrations have been found in private groundwater supplies in the U.S. Unfortunately, little Canadian data on waterborne radon levels exists, making it difficult to assess the importance of water as a source of radon exposure.

The presence of radon in water is governed by many factors, including the presence and levels of radium in water, radium in surrounding bedrock and soil, and radium deposits in household plumbing. For this reason, radium and uranium levels in water are not suitable indicators of the levels of radon in water.

The contribution of waterborne radon to air concentrations in homes can be estimated using a simple model derived by Nazaroff et al. (1987)[17] (as summarized in the BEIR VI report). The estimates derived in this report, as well as those in other studies, indicate that radon in water makes a small contribution to radon levels to indoor air. In order to validate these results, it would be useful to have data on radon levels in local underground waters, in addition to Canadian housing data (e.g. housing volumes and air exchange rates).

It is important to consider that a small incremental contribution of waterborne radon to airborne levels of radon can be important in homes that exceed or are close to exceeding the Health Canada guideline. Soil gas intrusion is the major source of radon in homes whereas, in most cases, waterborne radon is a much smaller contributor to indoor air radon levels. Because of this, efforts should be focussed on reducing the contribution of soil gas intrusion to indoor radon levels in homes where elevated radon levels exist both in water and air.

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