

An Interdisciplinary Population Health Approach to the Radon Health Risk Management in Canada

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Résumé : (traduction)

Le radon est un cancérigène qui se retrouve dans l'air intérieur et qui existe en quantités supérieures au niveau de référence du gouvernement fédéral (200 Bq/m³) dans environ dix pour cent des foyers canadiens. Le cancer du poumon provoqué par le radon tue plus de 3 000 personnes chaque année, ce qui représente 16 pour cent des décès annuels causés par le cancer du poumon au Canada. Le radon est la cause principale des décès attribués au cancer du poumon chez les non-fumeurs et la deuxième chez les fumeurs. Les enfants, les femmes et les fumeurs issus de groupes à faible revenu sont touchés de façon disproportionnée. Bien que le gouvernement fédéral ait réajusté le niveau de référence de 600 Bq/m³ à 200 Bq/m³ et que les gouvernements provinciaux aient révisé les codes de construction pour limiter l'exposition, les dernières avancées scientifiques pour adopter des stratégies de gestion du radon au Canada demeurent controversées.

Cette analyse se sert d'une approche intégrée axée sur la santé de la population pour examiner les relations et les interactions entre les déterminants de la santé de la population, tels que la biologie, la génétique, l'environnement, la profession, et les facteurs socioéconomiques qui influencent le risque du radon pour la santé. Les données recueillies et les politiques analysées en appliquant les principes éthiques et les principes de la gestion des risques ont mené à l'identification de stratégies de prévention efficaces, abordables à grande échelle et au niveau de la population. Les conclusions servent à améliorer la santé de la population en proposant des modalités d'intervention cruciales pour le Programme national sur le radon de Santé Canada.

Mots-clés :

Radon, risque pour la santé publique, déterminants de la santé, principes de la santé de la population, approche interdisciplinaire

Abstract:

Radon is a known carcinogen found in indoor air that exists at higher than the federal reference level (200 Bq/m³) in about 10% of Canadian homes. Every year, over 3,000 people die from radon-induced lung cancer, which accounts for 16% of annual lung cancer deaths in Canada. Radon is the leading cause of lung cancer deaths among non-smokers and is second among smokers. Children, women, and smokers from lower income groups are disproportionately affected. Although the Federal Government has reset the guideline (from the previous 600 Bq/m³ down to 200 Bq/m³) and provincial governments revised the building codes to limit exposure, there remain controversies with the latest scientific development in adopting strategies of radon management in Canada.

This review applies an Integrated Population Health Framework to look at the relationships and interactions between population health determinants such as biology and genetics, environment and occupation, and social and economic factors, that influence the health risk of radon. The evidence gathered supports policy analysis with the application of ethical and risk management principles that lead to the identification of efficient and affordable broad-based and population-level preventive strategies. The final inferences enhance the framework by adding critical intervention modalities to Health Canada's National Radon Program.

Keywords:

Radon, public health risk, determinants of health, population health principles, interdisciplinary approach

Introduction

Indoor air quality is one of the key determinants of health for Canadians as they spend over 90% of their time indoors (Setton et al., 2013). Having the world’s largest deposits of high-grade uranium, Canadian land emits soil gas radon that can seep into homes (Natural Resources Canada, 2014). This route of entry is enhanced by a growing negative pressure inside heated homes when the temperature falls outdoors (Henderson, Kosatski, & Barn, 2012). Radon degrades to emit radioactive alpha particles that attach to indoor aerosols, smoke, and particulate matters (CNSC, 2011). Upon inhalation, these alpha particles can induce DNA mutations in lung tissue, which can lead to cancer (Noh et al., 2016).

About 10% of Canadian homes have been identified as containing radon gas exceeding the federal reference level (200 Bq/m³; Henderson et al., 2012). Over 3,000 people die annually from radon-induced lung cancer, which accounts for 16% of all lung cancer deaths (Canadian Cancer Society, 2016). Radon gas is, therefore, the leading cause of lung cancer deaths among non-smokers and the second among smokers (Health Canada, 2014). Children, women, and smokers from lower socioeconomic status (SES) are disproportionately affected (Hill, Butterfield, & Larsson, 2006). While it is understandable that children have faster breathing thus inhale more air, and smokers have irritated lungs, it is still not clear why women are more susceptible to the effects of radon. A rough estimate determined the annual economic burden of radon-induced lung cancer to be about \$18 million in Canada alone (Health Canada, 2014).

In 2007, the Federal Government revised the original 1988 guideline for acceptable levels of radon (lowering it from 600 Bq/m³ to 200 Bq/m³), when studies established a link between exposure to high levels of radon and increased risk of developing lung cancer. The National Building Codes were also revised in 2010 to limit exposure. However, there remain notable controversies within the scientific community regarding radon risk management strategies in Canada. In particular, the reference level (a cut-off point to minimize risk) is still twice that of the 100 Bq/m³ recommended by the World Health Organization (2009). Moreover, research has indicated that there is no safe threshold level for radon and any amount of exposure may contribute to the development of lung cancer (Darby, 2005; Turner et al., 2011). As per Rose’s population strategy of prevention, shifting the distribution of a risk factor in a whole population will lower everybody’s risk and reduce the number of cases (Schwartz & Diez-Roux, 2001). Thus, spreading the radon management plan to address the population distribution of risk can lower the incidence of lung cancer cases at the population

level rather than only targeting low SES individuals. Based on the “optimization principle” of risk management, the International Commission on Radiological Protection (ICRP) recommends reducing radon levels as much as possible (2009). Therefore, not enforcing the federal guideline and only applying the building codes where radon level is high, are not the best solutions for radon risk management.

In order to address these shortcomings, this review applies an Integrated Population Health Framework (Figure 1, only “framework” hereafter) to the assessment and management of indoor radon to identify affordable, broad-based population-level measures aimed at preventing radon-induced lung cancer in Canada.

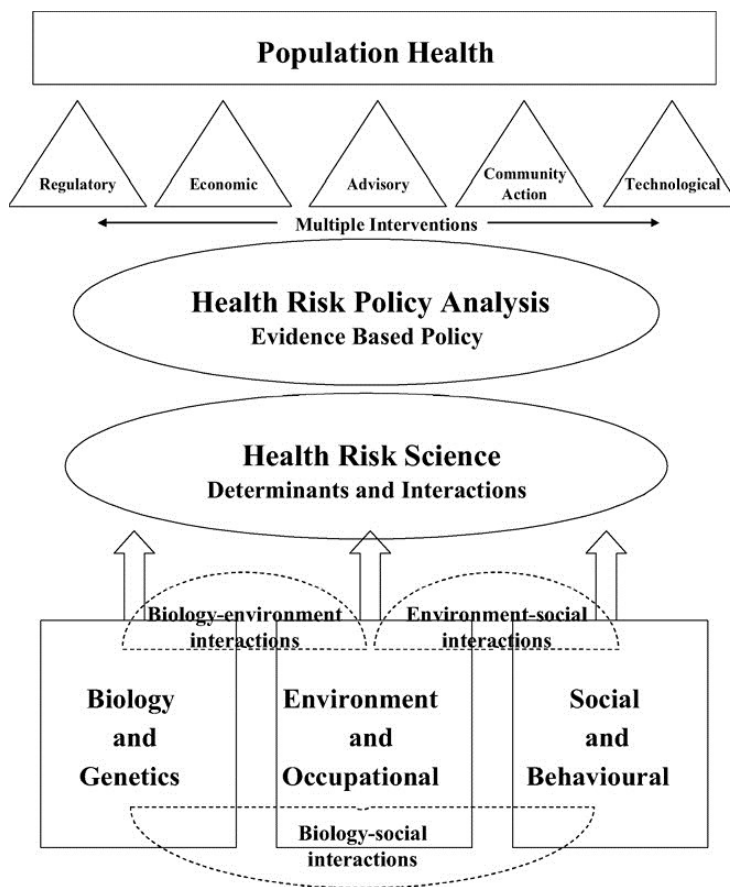


Figure 1

The integrated population health framework. Reprinted from “An Integrated Framework for Risk Management and Population Health,” by D. Krewski, V. Hogan, M. C. Turner, P. L. Zeman, I. McDowell, N. Edwards, and J. Losos, 2007, *Human and Ecological Risk Assessment*, 13, p. 1300. Copyright 2007 by Taylor & Francis Group, LLC. Reprinted with permission.

Integrated Population Health Risk Assessment and Management Framework

The framework is based on three basic sets of population health determinants: i) biology and genetic endowment, ii) environment and occupation, and iii) social and behavioral factors. This review will synthesize evidence on the interactions among these determinants to identify preventive strategies and to inform effective policy-making. The integrated nature of the framework also considers public health values, health economics, and ethics, as well as risk management principles (Krewski et al., 2007). These all are relevant to designing population health interventions and will be discussed in light of the evidence gathered.

Methods

A framework synthesis examined the relationships and interactions among the determinants that shape radon public health risk. The following electronic databases were searched for literature published between January 1990 and June 2016: EMBASE, MEDLINE, CINAHL, Environmental Sciences and Pollution Management, Sociological Abstracts, and Cochrane (Wiley). Search terms used were: “radon,” “public health risk,” “housing and indoor air pollution,” “population health,” “interdisciplinary approach,” “public

health,” “health disparity,” and “health equity.” Reference lists of identified articles were also searched for additional and relevant citations. Other material retrieved included official reports, guidelines, and statutes from the governmental, non- and inter-governmental websites such as Health Canada, Canadian Nuclear Safety Commission, Canadian Cancer Society, US National Institutes of Health, International Commission on Radiological Protection, United Nations Scientific Committee on the Atomic Radiation, and World Health Organization.

Search Results

A total of 1,440 documents (articles and grey literature) were identified (Figure 2); 1,132 articles were peer reviewed, including primary studies and systematic reviews. Title and abstract screening found 291 articles to be potentially relevant. The full texts of 50 articles were not retrievable. Of the remaining articles, 241 underwent in-depth relevance checking with the objectives of this review and 158 articles were excluded. Subsequently, 83 articles were reviewed for eligibility and 36 were eliminated after full-text analysis. A total of 47 articles met the inclusion criteria. Among these, 19 were reviews [14 high quality, five moderate quality (AMSTAR criteria)] and 25 were quantitative studies [12 high quality (experimental), 11 average (case-control and

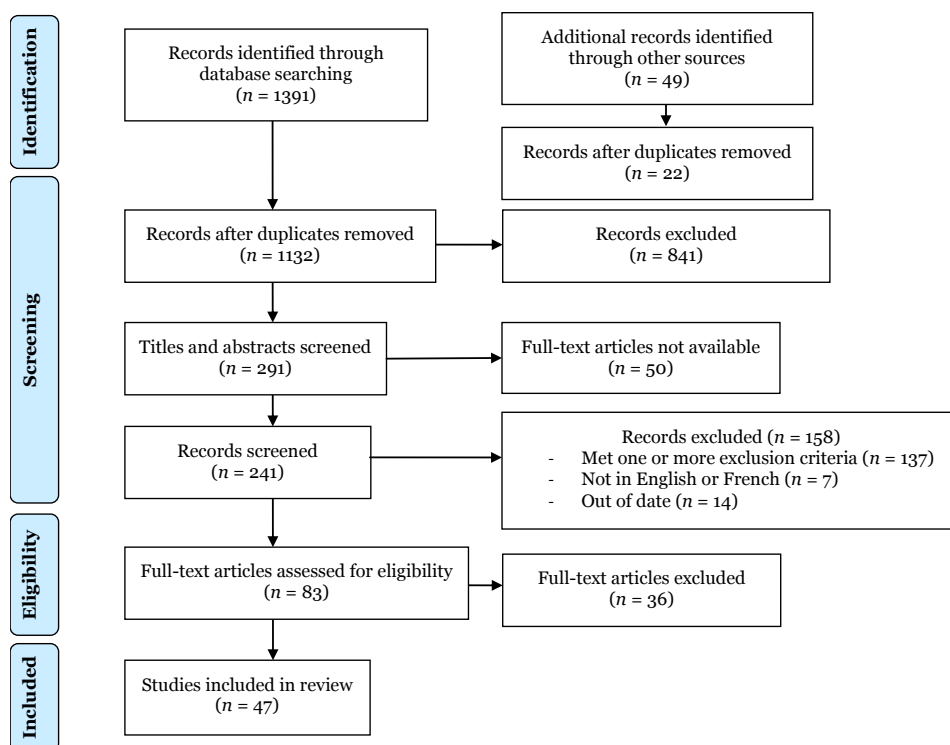


Figure 2 Prisma flow diagram.

cohort), and two weak (surveys)]. Only one qualitative study was a high-quality review. Two mixed methods studies were also included, one of which was of high quality and another of moderate quality. There were 11 reports, two statutes, one glossary, one guideline, one essay, one editorial, one commentary, one conference paper, and three books also included to minimize the likelihood of publication bias.

Review Outcomes

Evidence garnered from the review were fed into the framework to explain the relationships and interactions of radon exposure to the three sets of population health determinants as follows:

1. Biology and genetic endowment: Feeble biological construction (Chauhan et al., 2012; Robertson, Allen, Laney, & Curnow, 2013) and genetic vulnerability (Druzhinin et al., 2015; Madas & Varga, 2014) make some people more susceptible to adverse environmental outcomes than others. Likewise, individuals with robust immunity are less affected than those with weak or hypersensitive immune systems (Lin et al., 2004). Similarly, the presence of certain genetic traits can make some people more vulnerable to hazards (Kiyohara et al., 2004). Hill et al. (2006) noted that risk varied based on age and sex; children are more affected than adults due to a higher respiration rate. Men being more aware of the risks of radon exposure, will test houses more often but are less concerned and less affected compared to women (Poortinga, 2008, 2011). Temporal trends in lung cancer mortality are increasing for women while decreasing for men (Branion-Calles et al., 2015). However, it is not yet clear whether this is due to the increasing rates of smoking among women or due to their spending more time indoors.

2. Environmental and occupational: Radon degrades at different speeds in different geographical, seasonal, and meteorological conditions. Because exposure is a function of the degradation rate, the risk is determined by these conditional factors (Appleton, 2007; Chen & Marro, 2011; El-Zaher, 2011). The lunisolar gravitational tides influence the geological environment and this, in turn, affects radon release and further degradation into alpha particles (Zakhvataev, 2015). The radon infiltration rate into homes increases as outdoor temperatures decrease because the warmer indoor environment creates a pressure differential that draws soil gas into the building (Henderson et al., 2012). Therefore, increasing airtightness of dwellings in pursuit of energy efficiency will increase radon emission from the ground (Vardoulakis et al., 2015). Exposure will also depend on the type of ventilation system used (exhaust fan or heat and energy recovery ventilators; Jerrett et al.,

2005). Radon exposure varies with the change in occupation as certain occupational groups such as miners are particularly affected while working in closed mines (Field et al., 2006). Likewise, the status of being a tenant or house-owner has differential impacts as tenants have limited resources and authority to take remedial actions (Beck et al., 2013; Poortinga et al., 2011).

3. Social and behavioural: In North America, over 30% of homes are rented, and about 70% of tenants are young adults with children. This group is typically of low SES and is less likely to have knowledge about the risks of radon exposure or the means and rights to have their dwellings tested and repaired (Hill et al., 2006; Larson et al., 2011). There are clear socioeconomic differences in radon-related awareness, risk perceptions, and behaviors. People from lower SES (Kendall et al., 2016) and rural areas (Hill et al., 2006) are less likely to be aware of the risks of radon exposure. Time-series studies of exposure to air pollution found a higher risk of all-cause mortality for people of lower SES (Lin et al., 2004; Villeneuve et al., 2003). Adults in Canada spend 93.75% of their time indoor, either working, studying, playing, or just maintaining a sedentary lifestyle mainly due to the long winter season (Setton et al., 2013). Whereas increased mobility experienced in the summer, decreases the extent of exposure (Pope & Dockery, 2006). Lastly, smoking has a possible synergistic effect with radon, making smokers up to seven times more vulnerable to lung cancer risk (Lubin & NIH, 1994), increasing life-years lost threefold compared to never-smokers (Noh et al., 2016).

Interactions between the determinants

1. Gene-environment interactions: Genetic factors influence specific respiratory health outcomes associated with air pollution and lung cancer (Kiyohara et al., 2004). Although certain individual genes can only be activated by specific environmental triggers (Ruano-Ravina et al., 2014), a genetic correlation with radon has yet to be established.

2. Biology and social interactions: Radon-induced lung cancer is highly prevalent among miners who are also habitual smokers compared to non-smokers (Krewski et al., 2005). Furthermore, more social interaction is associated with more resources and social capital that boost immunity; thus, people with higher SES are affected less often than their low SES counterparts (Lin et al., 2004; Villeneuve et al., 2003).

3. Biology-environment interactions: Radon exposure occurs in houses that have cracks in the basement and are exposed to the soil (Jerrett et al., 2005; Lin et al., 2004; Villeneuve et al., 2003). Oftentimes, these houses will have more dust, aerosols, combustion by-products, and tobacco

smoke, which will mix with radon decay products (RDP) to get fixed in lung mucosa that is already irritated by tobacco smoking (Schmid, Kuwert, & Drexler, 2010).

4. Environment and social interactions: People of lower SES usually live in older houses that are under-maintained. They are less likely to change an old furnace and clean ducts regularly. In contrast, people with a higher SES maintain their houses and control or even modify their environment with newer technologies (Vardoulakis et al., 2015). However, a recent study in the UK shows an inverse relation to SES, whereby affluent houses that are air-tight and drought-proof have higher levels of radon (Kendall et al., 2016).

5. Behavioural and environmental interactions: Individual behaviour to risk responses such as closing windows to avoid crime or sleeping in the basement to avoid traffic noise, modifies the living environment, thus increasing the level of exposure to radon (Briggs, Abellan, & Fecht, 2008).

Radon health risk science

This section summarizes the review results by assessing the gravity of the problem and proposing solutions that prove efficacious in mitigating radon public health risk. As noted from early quantitative studies (Darby et al., 2005), the average annual exposure to indoor radon in Canada is 1.8 mSv, which is higher than the worldwide average dose of 1.2 mSv (UNSCEAR, 2011). The Lifetime Excess Cancer Risk (LECR) is 23,655 per million people in Canada; thus, radon poses the highest risk among the most common environmental carcinogens (Henderson et al., 2012). Similarly, Chen and Marro (2011) found radon equilibrium factors to be higher in both outdoor and indoor atmospheres in Canada. Despite the gravity of the risk, only 42% of homeowners have heard about radon and 5% have tested for it (Statistics Canada, 2015). Yet, according to a Canadian survey, there has been a significant rise in lung cancer risk due to residential level exposure.

The level of awareness about the risk is critical to scaling up the preventive programs (Beck et al., 2013). Risk perception raises concern and drives individuals to make proactive decisions to mitigate the risks. Evidence shows that low-income rural citizens do not understand the harmful consequences of radon exposure due to lack of access to adequate information (Hill et al., 2006). Disagreement also exists between experts and lay people about the gravity of radon risk. Therefore, risk communication approaches should consider people's psychometrics, as well as the social and cultural contexts that shape their risk perception (Poortinga, Bronstoring, & Lannon, 2011). Krewski et al.

(2006) previously identified the psychometrics that covered the perception of risk gravity: immediacy and severity of the effects, newness or uncertainty about the risk, voluntary nature of exposure, and the characteristics of individuals. Moreover, personal knowledge, beliefs, and worldview also play important roles (Poortinga et al., 2008). Social contexts can either amplify or attenuate the effects depending on factors such as access to media, education, and social position (Hill et al., 2006; Larsson et al., 2011). It is easier for public health authorities to encourage testing and remediation when homeowners are convinced that their property and its inhabitants have an elevated risk (Henderson et al., 2012). Such was the case in Winnipeg, where homeowners were unmotivated to act when the radon level reached 1100 Bq/m³, but once they were made aware of the health risks, they became willing to pay for remediation even at a level of 702 Bq/m³ (Spiegel & Krewski, 2002).

As per above evidence, radon exposure is a serious public health problem. People adopt testing and remediation measures widely once they are aware. Nevertheless, effective population health prevention policy should employ multiple approaches that are evidence-based, negotiated and accepted by the stakeholders, economically feasible, and ethically sound (Chen, Moir, & Whyte, 2015; Hystad et al., 2014).

Discussion and health policy analysis

The traditional knowledge-driven models where new knowledge creates pressure to adopt a policy is not ideal for the issue of radon. Considering the long-term effects of radon, public health professionals need to explore and integrate problem-solving, as well as interactive and political models of policy formulation, by synthesizing evidence from a variety of sources, engaging the vulnerable population, and raising awareness to create a social climate that is favourable for the policy (Nutbeam, Harris, & Wise, 2010). Milio's (1987) framework considers the broad social, economic, and political contexts beyond the views of the public to drive a policy initiative, whereas the 3-i framework from Political Science contemplates three specific actors for policy change: interest, idea, and institution (Hall, 1997). Accordingly, identifying the vested interests, conflicting values, ideas, and perspectives of radon stakeholders as well as exploring the capacity and roles of mandated institutions and organizations are all crucial for leveraging radon health risk policy.

Economic analysis

There has been no recent economic analysis on radon in Canada. Letourneau et al. (1992) conducted a comparative economic analysis and demonstrated that a universal radon

program would impose an unjustifiable financial burden; hence, they recommended some alternative courses of action that include imposing building codes for all new constructions, and testing and mitigation of houses at the point of sale. However, the latter does not cover rented and community houses that seldom are put up for sale, thus excludes over 30% of residents from the program. To achieve the population-wide goal of radon risk reduction, we should look for suitable, pro-equity interventions that will have maximum coverage.

Analysis of ethical principles

The ethical principles of radon public health risk management primarily relate to social justice, as there is an issue of health inequity. To this end, strategies should:

- i. Adopt a fair process of decision-making that is unbiased and objectively covers all vulnerable dwellings as far as possible.
- ii. Use the limited risk management resources optimally to maximize benefit.
- iii. Foster informed risk decision-making by providing stakeholders with full access to the necessary information.
- iv. Be flexible and evolutionary to accept new scientific evidence.
- v. Be aware that complete elimination of radon risk is not possible even after employing all efforts (Krewski, 2015).

Radon health risk management: Multiple interventions

Drawing on the evidence synthesized by Krewski (2015), actions are required at multiple levels to reduce radon exposure and prevent lung cancer. In addition to the five actions mentioned in the framework, the following health communication and population-level preventive measures (suitable for lower-income households) are suggested that enhance the framework:

1. Regulatory action: Many European countries have introduced regulations to protect their populations from the risk of lung cancer associated with radon exposure (Bohicchio, 2008; Colgan & Gutierrez, 1996; Synnott & Fenton, 2005). In Canada, no law requires homeowners to test radon levels, minimize exposure, or disclose test results, apart from the limited building and construction codes enforced in certain high radon areas in Ontario and Quebec (CELA, 2014). There is an urgent need to pass a comprehensive radon act, imposing mitigation measures on

all house owners and making it an essential condition to legalize all real-estate transactions.

2. Economic action: As mentioned, testing of homes at the time of sale and mitigation when necessary, have found to be the most cost-effective option (Letourneau et al., 1992). In this regard, the provincial government could provide a reasonable rebate to homeowners to compensate the cost of mitigation. However, this is not the solution for community houses and buildings that are rarely up for sale.

3. Advisory action: At the federal level, the guideline on radon is advisory, meaning that compliance is voluntary, and the responsibility for testing, remediation, and associated costs rests with the property owners. There are three different approaches: a) Guideline approach: Conducting research on the effects of radon exposure and evaluating the measurement techniques, thus, refining the guidelines. b) Consultative approach: Persuading homeowners to mitigate radon risks. Providing homeowners with a guide booklet can be an active approach by dedicated environmental health professionals. c) Administrative approach: Here, the local government assumes responsibility for designing and implementing formal safety standards and enforcing them through specialized agencies (Krewski, 2015). There could be an inspectorate within Health Canada to randomly inspect susceptible houses, test for radon, and advise on remediation.

4. Community action: Under planned community initiatives, a “Radon Committee” could engage members of the community in dialogue to increase awareness about the presence of indoor radon, radon health risks, cost-effectiveness of testing, and decision making for mitigation, where necessary. This committee could inform people that they are required by law to test and mitigate radon levels when buying or selling a home.

5. Technological action: The effectiveness of a radon remediation technique depends on the building architecture. As per current evidence, placement of a radon-proof slab during construction or sub-slab depressurization in existing homes is the gold standard for radon prevention and mitigation, and should be included in the guideline (WHO, 2009).

6. Risk communication: Uncertainty regarding the risk associated with radon should no longer be a challenge in persuading people. However, there remain constraints regarding costs of mitigation, lack of incentives, and inadequate access to information for residents (Ganong et al., 2008). It must involve having a clear understanding of people’s knowledge and beliefs about the issue (Nutbeam, 2010). An effective risk communication campaign should

convey the message in a manner that the gravity of risk is understood up to the point where people are moved to act (European Commission, 2011). An effective strategy should engage stakeholders including government agencies, industries, unions, professional organizations, public interest groups, media, as well as individual residents (Krewski, 2015). Health Canada has been using social media, workshops, webinars, public forums, poster contests, trade shows, and conference events to communicate radon risk (Cheng, 2016). Regrettably, these communication efforts have not made a significant impact. Therefore, a better risk communication strategy should be based on sound theories to target behavioral issues that people can adopt gradually

via their means and capacities. A combination of health belief theory and social marketing principles could be a good strategy to convey the gravity of the situation as well as to explain the benefits of mitigation. In this regard, Cheng (2016) stressed the identification and demystification of certain myths that are prevalent about radon. These include the reality of the mere presence of radon, the gravity of the risk, relations of its indoor concentration with human behavior, and the efficiency of mitigation. He also emphasized the need for contextual adaptation and engagement of the stakeholders to work together in sharing knowledge, expertise, and resources (Cheng, 2016).

Table 1

Preventive actions. Adapted from “Radon Testing for Low-Income Montana Families,” by L. S. Larsson, P. Butterfield, W. G. Hill, G. Houck, D. C. Messecar, and S. Cudney, 2011, *Proceedings of the 2011. International AARST Symposium*. Retrieved from http://www.aarst.org/proceedings/2011/RADON_TEST-ING_FOR_LOW-INCOME_MONTANA_FAMILIES.pdf. Copyright 2011 by AARST. Adapted with permission.

Know the Risk	Every home has radon. It’s harmful at any level and adverse health effects are irreversible.
Talk and Exchange	Make radon a topic in the social discussion! Give radon test kits as a gift.
Move Up!	Avoid basement and ground level apartments. Move up kids’ bedrooms and play areas.
Talk to the Landlord	If renting, talk to the landlord or property manager about measuring indoor radon level.
Test your Home	Ask homeowners whether a home is tested by a radon professional every two years.
See Results	Ask to see results of radon measurements for children’s schools and day-care facilities.
Quit Smoking	If radon is higher than the guideline level, it’s one more reason to quit!
Risks and Rewards	Consider the risks of having home-gym equipment in a high-radon basement.
Plan Saving	If you can’t afford mitigation right away, make a saving plan, your lungs are worth it!
Clean Your Air	Place a surgical mask over desktop fan.
Shun Wood Furnace	Buy a portable air cleaner rather than use wood for heating.
Open Doors-Windows	Open doors and windows whenever the weather allows.
Employ your Furnace	Use high-efficiency filters to block radon particles.
Run a Fan	Run a fan with an electronic motor on a low-speed setting to clean indoor air.
Step Out	When possible, consider spending more time outdoors.
Open Vents	Increase ventilation under the house by opening foundation vents.
Seal Cracks	Control indoor radon by sealing cracks and openings in the basement.
Place a Membrane	Decrease radon by putting a plastic sheet over exposed soil in the cellar.
“Do-It-Yourself”	Testing is easy; search YouTube for “DIY home radon test.”

Population-level preventive actions

Following Rose's principle, radon risk management should include broader population-level preventive actions that could be scaled-up to maximize the benefits (Milat et al., 2014). Table 1 below displays messages, activities, and strategies targeting low-income families that can increase radon program uptake.

Conclusion

This framework review makes clear the significant public health risk that radon exposure poses via its ability to induce DNA mutations even at a concentration below the current reference level. It captures the determinants shaping radon health risk and synthesizes scientific evidence to inform policy decisions and demonstrate a need for multilevel interventions. It identifies what is known so far, what works, and what is inconsistent with the latest scientific developments.

Finally, the framework suggests recommendations for action. These include cost-effective population-level measures that can be encouraged through Health Canada's National Radon Program, and suggestions that can be applied directly to the low-income households.

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