A Population Health Approach to Examine Ottawa-Gatineau Residents' Perception of Radon Health Risk

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Preface

Abstract

Background: Radon is a high impact environmental pollutant and is the second leading cause of lung cancer in Canada. Despite the gravity of the health risk, residents have inadequate awareness and have taken minimum preventive actions. The success of any population-level health awareness program is contingent on the views and actions of key decision makers at the household level. People's perceptions of the risk should inform health communication messaging that aims to motivate them to take preventive measures. The objective of this study was to measure the quantifiable associations and predictions between perceptions of radon health risk and their preventive actions; to explore and examines the social determinants that enable and hinder the adoption of preventive measures. Additionally, the best effective radon control systems for both the new and existing houses and relevant policy implications have been examined.
Methods: A mixed methods study consisting of surveys (n=557) and qualitative interviews (n=35) was conducted with both homeowners and tenants of Ottawa-Gatineau areas. Descriptive, correlation and regression analyses addressed the quantitative research questions. Thematic, inductive analysis identified themes in the qualitative data. A mixed methods analysis triangulate both results. A registered systematic review of radon interventions around the world was conducted and radon policy analysis was done by applying interdisciplinary frameworks.
Results: Residents' perceptions of radon health risk, smoking at home, social influence, and care for family significantly correlated with their intention to test for radon; the same variables predicted their protection behaviours. Residents obtained information on radon from the media, individual search, workplace and social networks. Residents who had dual - cognitive and emotional awareness of the risk, were motivated enough to take action. Having an understanding of the risk, caring for family, knowing others who contracted lung cancer and being financially capable were enablers for action. Obstacles included lack of awareness, cost of mitigation, lack of home ownership and potential stigma in selling the house. Residents attributed primary responsibility to public agencies for disseminating information and suggested incentivizing and mandating actions to promote preventive measures. Indoor radon is best controlled by installing an active SSDS with additional measures to seal any entry points in the foundation. The policy analysis generated a list of recommendations that can be implemented through multisectoral systems level actions to address the social determinants of risk distribution.
Conclusions: Residents do not get the crucial information on radon health risk and report barriers in testing and engaging in protective action. Risk perceptions are subjective and influenced by micro and macro level factors. Inducing protective action to reduce risk requires comprehensive interventions taking into account dual perceptions of the threat. Future research can explore the dual aspects of risk perception and examine the contents of the risk communication message. Policy should address the shared responsibility of both governments and residents in tackling the issue with reasonable incentives and mandatory regulations.

Keywords: Population Health, Radon, Risk Perception, Mixed Methods, Policy, Management.

Résumé

Contexte : Le radon est un polluant environnemental à fort impact sanitaire et constitue la deuxième cause de cancer du poumon au Canada. Malgré la gravité du risque qu'il représente pour la santé, les résidentes et les résidents sont souvent mal informés sur les conséquences sanitaires qu'il représente et prennent généralement peu de mesures préventives contre celui-ci au domicile. Le succès de tout programme de sensibilisation à la santé qui tente d'agir sur le plan populationnel dépend des perceptions et des actions des décideurs clés au niveau des ménages. Les perceptions qu'ont les individus du risque devraient informer les messages de communication de santé visant à les inciter à prendre des mesures préventives. L'objectif de cette étude était double : (1) de mesurer par des méthodes quantitatives l'influence des perceptions du risque pour la santé liée au radon sur les actions préventives adoptées ; (2) d'explorer et d'examiner les déterminants sociaux qui facilitent ou entravent l'adoption de mesures préventives liées au radon au domicile. De plus, l'efficacité de différents types de systèmes de contrôle du radon pour les maisons neuves et existantes et leurs implications sur les politiques a été examinée.
Méthodes : une étude avec des méthodes mixtes a été réalisée par un sondage en ligne (n = 557) et des entretiens (n = 35) menés auprès de propriétaires et de locataires de la région d'Ottawa-Gatineau. Des analyses descriptives, de corrélation et de régression ont d'abord été effectuées sur les questions de recherche quantitative. L'analyse thématique inductive des données qualitatives a ensuite permis de déterminer les thèmes pertinents. La triangulation des données a été possible par la mise en commun des données. Enfin, une revue systématique a été réalisée sur les interventions et les politiques sur le radon présentes à l'échelle internationale en utilisant un cadre d'analyse interdisciplinaire.
Résultats : Les perceptions des résidentes et des résidents concernant les possibles risques pour la santé liés au radon, le tabagisme à la maison, l'influence sociale et les soins apportés à la famille sont des variables significativement corrélées à leur intention de dépister le radon à la maison ; les mêmes variables ont prédit leurs comportements de protection contre le radon. Les résidentes et résidents ont obtenu de l'information sur le radon principalement par les médias, par des recherches individuelles, sur les lieux de travail ainsi que par les réseaux sociaux. Les résidentes et résidents qui avaient une conscience à la fois cognitive et émotionnelle du risque sanitaire que représente la présence de radon au domicile étaient suffisamment motivés pour agir contre celui-ci par des mesures préventives. En ce sens, connaître les risques sanitaires que représente le radon, souhaiter protéger sa famille, connaître dans son entourage des personnes qui ont contracté le cancer du poumon et être financièrement apte à prendre des mesures préventives ont été des catalyseurs d'action dans la prévention des impacts sanitaires du radon à domicile. Les obstacles comprenaient le manque de sensibilisation aux risques, le coût des mesures d'atténuation, le fait d'être locataire et la stigmatisation potentielle de la présence de radon lors de la vente de la maison. Les résidentes et résidents ont suggéré que les agences publiques sont les principaux responsables dans la diffusion d'information concernant le radon et ils ont proposé des pistes d'actions pour promouvoir les mesures préventives dans les domiciles. Le meilleur moyen de contrôler le radon intérieur consiste à installer un système intégré d'aspiration sous la dalle ainsi que des mesures supplémentaires pour sceller les points d'entrée du radon dans la fondation du bâtiment. L'analyse systématique des politiques a généré une liste de recommandations pouvant être mises en œuvre au moyen d'actions multisectorielles afin de prendre en compte les déterminants sociaux dans la répartition des risques sanitaires.

Conclusion : Les résidentes et résidents ne reçoivent pas les informations cruciales sur les risques sanitaires que représente le radon au domicile et rencontrent des obstacles qui les empêchent de prendre des mesures et des actions pour les protéger. Les perceptions du risque sont subjectives et ils sont influencés par des facteurs sur le plan micro et macro. Promouvoir des mesures de protection pour réduire les risques sanitaires associés au radon nécessite des interventions intégrées prenant en compte la double perception de la menace. D’autres recherches gagneraient à explorer davantage cette double perception du risque et d’examiner le contenu des messages de communication du risque. Les politiques devraient aborder la responsabilité partagée des gouvernements et des résidentes et résidents dans la résolution de ce problème, notamment par de la réglementation et des normes à caractère incitatif et obligatoire.
Mots clés : Santé de la Population, Radon, Perception Des Risques, Méthodes Mixtes, Évaluation des Risques, Politique, Gestion.

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Acknowledgement

I am grateful to all who helped and supported me in different ways throughout my doctoral program and in writing this dissertation. First of all, I would like to acknowledge the contribution of my study participants for this doctoral research project. Their stories, experience, perspectives and wisdom flourished my knowledge, ways of thinking and going ahead. So, my hearty gratitude to all of them and their near and dear ones. Without their genuine interest and support, this work would have never been done.

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Most gratefully,

Selim M. Khan

Collaboration and Contributions of Supervisors and Co-authors

This dissertation was written under the direct supervision of my supervisor Dr. James Gomes and co-supervisor Dr. Samia Chreim. They have guided, revised the dissertation chapter by chapter, provided feedback and cleared the final draft before submission.

The manuscript of the first published article – scoping review was prepared and written by me and critically reviewed and feedback provided by Dr. James Gomes as a co-author.

The manuscript of the second quantitative article was prepared and written by me. I did the data analysis but consulted and took guidance from Dr. James. The manuscript was read, and feedback provided by Dr. James Gomes, Dr. Daniel Krewski and Dr. Raywat Deonandan- all three are co-authors with me. I also received valuable input on the organization of the article and linking ideas between chapters from Dr. Samia that helped to improve the article, but she refused to be included among the co-authors saying that she does not do quantitative research.

The qualitative data was collected, analyzed and initial codes assigned by me; I also prepared the first draft of the manuscript. Dr. Samia Chreim critically reviewed and revised the draft and added her inputs to improve it. Both authors met regularly and discussed data analysis, interpretation and decided on the themes. Thereby, a final draft was prepared by me incorporating feedback from Dr. Samia. It was again discussed and agreed by both authors. Dr. Chreim is the only co-author in this article.

A systematic review protocol was developed jointly by Dr. James Gomes and me. It was registered with the National Institution of Health Research, UK. Both of us searched literature separately, met regularly to discuss document selection and their final inclusion in the review. I prepared the manuscript, but it was critically reviewed, and feedback provided by Dr. James and Dr. Krewski; thus, they both are the co-authors.

Compliance with Ethical Standards

The University of Ottawa's Health Sciences and Science Research Ethics Board (REB) approved the study and data collection protocols (file number: H10-17-03) on December 13, 2017. We duly secured informed written consent for participation, voice recording and direct quoting. We assigned a number to each participant to maintain anonymity and excluded any identifying information from the quotes. A copy of the ethics approval and approved consent forms are annexed.

Copyright

Dedication

I dedicate this thesis to my mother, who taught me the first lesson of my life. To my father, whose best wishes inspired me and still make me look back. And my wife and daughters, who are giving me company all the way on my quest to explore new academic horizons.

Note to Readers

As agreed with my thesis advising committee, my dissertation is article-based, and there should be a maximum of four articles either published or on the way to publication. Therefore, *this thesis paper is not a monograph.* Instead, following the departmental guideline on the article-based thesis, I linked the articles in this document. Two of the four articles have already been published and two others are under review with the BMC Public Health and Science of Total Environment. The four articles or papers are:

1. Khan SM, Krewski D, Gomes J, Deonandan R. Radon, an invisible killer in Canadian homes: Perceptions of Ottawa-Gatineau residents. Published in the Canadian Journal of Public Health, 110(2), 139-148. Available from: http://link.springer.com/article/10.17269/s41997-018-0151-5
2. Khan SM, Gomes J. An Interdisciplinary Population Health Approach to the Radon Health Risk Management in Canada. Published in the Interdisciplinary Journal of Health Sciences. 8(1), 32-43. Available from: https://doi.org/10.18192/riss-ijhs.v7i1.1872
3. Khan SM, Chreim S. Residents' perception of radon health risks: A qualitative study. Accepted for publication in BMC Public Health with assigned DOI: 10.1186/s12889-019-7449-y
4. Khan SM, Gomes J. Krewski D. Radon interventions around the globe: A systematic review. Published in Elsevier journal Heliyon on 27 May 2019. Available from https://authors.elsevier.com/sd/article/S2405844019336813

Although articles are copied and pasted as were published or submitted, the reference styles are changed to APA style to maintain consistency so that readers would not find different styles while going through this document. Similarly, the tables and figures are numbered serially as appeared in this paper. However, there would be repetitions of some information provided in the introduction sections of articles as they meant to set the background for publication in different journals.

In addition to the articles, I added a general introduction, rationale of this project, background information, conceptual and theoretical frameworks, a focused literature review, methodology and methods with some opening comments before each chapter.

Besides, quantitative and qualitative analyses presented in two articles, a separate mixed methods analysis of both quantitative and qualitative findings is presented. This followed the interpretations where the results complemented or contradicted each other and culminated in a global discussion. I also added policy analysis and recommendation, a general conclusion and the future research direction sections. Overall, I followed the APA (American Psychological Association, 6th edition) style in citing and reference listing.

Due to working with different academics, I followed their disciplinary norms. Thus, the third person is used in the quantitative part, the first person for qualitative analysis and as per convention, plural (we) is used in the systematic review, as two researchers searched literature.

The appendices contain the copies of ethics approval and other relevant documents. There is a glossary of terms used after the reference list.

The table of content is navigable – readers can click on any item to go over the text.

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Legends

ALARA: As Low as Reasonably Achievable
APCHQ: Association Provinciale Des Constructeurs D'Habitation Du Québec
Atlas.ti: The Qualitative Data Analysis & Research Software
BEIR VI: Sixth Committee on the Biological Effects of Ionizing Radiation
Bq: Becquerel
CAREX: CARcinogen EXposure
CARST: Canadian Association of Radon Scientists and Technologists
CBO: Community Based Organization
CELA: Canadian Environmental Law Association
Ci: Curie
CMA: Census Metropolitan Area
CNSC: Canadian Nuclear Safety Commission
DNA: Deoxyribose Nucleic Acid
GSAED: Graduate Students Association (Association Des Etudiants Diplomes De L'Universite D'Ottawa)
IAEA: International Atomic Energy Agency
IARC: International Agency for Research on Cancer
ICRP: International Commission on Radiological Protection
LR: Likelihood Ratio
MMR: Mixed Methods Research
mSv: millisievert
NCRP: National Council on Radiation Protection and Measurements
NRC: National Research Council
NRP: National Radon Program
PCi: PicoCurie
PMT: Protection Motivation Theory
RDP: Radon Decay Products (Radon Progeny)
REB: Research Ethics Board
SES: Socioeconomic Status
SPSS: Statistical Package for the Social Sciences
Sv: Sievert
UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation
WHO: World Health Organization

Chapter One: Introduction

Why is Radon a Public Health Issue?

Indoor air quality is one of the determinants of health for Canadians as they spend more than 90% of the day indoors (Setton et al., 2013). Canada contains the largest uranium deposits in the world (Natural Resources, 2014); its soil emits much radon gas that seeps into buildings mainly through foundations (Health Canada, 2014). The rate of entry is enhanced by a growing negative pressure inside heated homes in winter when the temperature falls outdoors (Fro ka & Jilek, 2014). Radon gas builds up in enclosed areas and degrades to emit radioactive alpha particles that upon inhalation, induce mutations in human DNA and can lead to cancer formation (Gustavino et al., 2014; ICRP, 2007). Radon is the primary source of lifetime radiation exposure (Schauer & Linton, 2009) that correlates with increased prevalence of lung, blood, kidney, skin and some types of childhood cancers (Darby et al., 2005; Henshaw, Eatough, & Richardson, 1990; Marsh & Bailey, 2013; Teras et al., 2016).

As per the Global Burden of Disease Study 2010 (Lozano et al., 2012), worldwide lung cancer mortalities has increased by 47% between 1990 and 2010. Uses of tobacco causing about 85% of all these deaths and the remaining 15% are attributed to indoor radon and outdoor air pollutions. However, radon having a synergistic effect on smoking related lung cancer, the global population attributable factors of lung cancer mortality in 2012 from radon (up to 16.5%) is more than that is (12.8%) attributed to outdoor air particulates attributable (PM2:5) (Evans et al. 2013). Therefore, controlling residential radon is crucial in tackling the global burden of lung cancer mortality.

The World Health Organization ranked radon as the fifth leading cause of mortality in 2010. Gaskin et al. (2018a) analyzed an updated database of national radon exposures from 66 countries and estimated the global population attributable burden of lung cancer mortality attributable to residential radon in 2012. The population attributable risk (PAR) of lung cancer mortality found to be 16.5%, 14.4%, and 13.6% for the exposure–age–concentration (EAC) model (BEIR VI), the Hunter model, and the Kreuzer model, respectively. The number of radon-attributable lung cancer deaths for all 66 countries totaled 226,057 in 2012 and represent a median of 3.0% of total cancer deaths. Thus, the concluded that globally residential radon is responsible for a substantial proportion of lung cancer deaths (Gaskin et al., 2018a).

In Canada, depending on the regions, about 7 to 19% of homes have radon gas above the federal reference level (Health Canada, 2012; Henderson, Kosatski, & Barn, 2012). In Ontario alone, every year 1,300 radon-induced lung cancer cases are diagnosed, and among them, 850 people die. By comparison, the deadly indoor pollutant carbon monoxide kills only 11 Ontarians in a year (Public Health Ontario, 2016). Over 3,200 Canadians die annually from radon-induced lung cancer, which accounts for 16% of all lung cancer deaths in the country (Canadian Cancer Society, 2016; Chen, Moir & Whyte, 2012). Thus, radon gas is the leading cause of lung cancer mortality among non-smokers and the second among smokers (Health Canada, 2014). Children, teens, women, and smokers from lower socioeconomic groups are disproportionately affected (Chen, 2013; Darby et al., 2005; EPA, 2014; EPA, 2015; Hill, Butterfield, & Larsson, 2006; Krewski et al., 2005; Lubin et al., 1995). The direct annual health care cost of radon-induced lung cancer has been estimated to exceed $17 million in Canada (CELA, 2017).

The National Radon Program (NRP) of Health Canada has been providing leadership in developing and updating the national reference level for radon, producing advisory documents, testing across Canada, mapping radon zones, training and accrediting radon professionals, outreaching with public education and conducting public opinion surveys, and directing the National Building Code (Health Canada, 2014). Besides, in partnership with all levels of governmental and non-governmental organizations, NRP has been disseminating radon health risk[1] messages using diverse media since 2008 after acceptance of the revised guideline on radon.

Despite various efforts, the program lags behind the target public uptake. According to the latest Household and the Environment Survey, 55% of Canadian households have heard about radon; however, only 6% of them have taken any preventive action (Statistics Canada, 2016). Bridging the gap between risk awareness and actual adoption of preventive behaviour presents a challenge for public health professionals (Nicol, Rideout, Barn, & Kosatsky, 2015; Spiegel & Krewski, 2002). So far, practitioners in different countries assumed that programs

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[1] 'Radon health risk' is defined as the human health risk from exposure to the soil gas radon (WHO, 2009). The Committee on Health Risks of Exposure to Radon (BEIR VI, 1988), based on pooled miners data, determined that the risk of mortality from lung cancer varied linearly with cumulative radon exposure depending on age of the victim, time since exposure, and either radon concentration or duration of exposure (National Research Council, 1999).

offering better-communicated information, enforced guidelines, and tax rebates would be among the best solutions for radon health risk management. However, studies in the United States (Hahn, 2014), the United Kingdom (Poortinga, Bronstering, & Lannon, 2011), and Ireland (Dowdall, Fenton, & Rafferty, 2016) showed that taking regulatory actions, offering rebates, and even providing free test kits and services did not significantly improve the program uptake. Thus, a key question - how to motivate the target population individually and collectively? - Remains unanswered.

Even after informing residents that their houses might have a high level of radon that may pose a serious health threat, protective actions remained low (Field et al., 1993). Research in psychology and neuroscience have described the subjective and objective understandings of risk and determined a dual- cognitive and affective risk perception process (Beck & Frankel, 1981; Janz & Becker, 1984; Slovic, Finucane, Peters, & MacGregor, 2004; Weinstein, 1988). Social science research has identified that the success of any population-level awareness program is contingent on the views and actions of key decision makers at the household level (Lorang, 2001).

We assumed that attempts to reduce health risks would benefit from an understanding of people's perception of the risk, as well as, the views and actions related to its management. There is a dire shortage of scholarship on the public perception of radon health risk in Canada. Therefore, in this study, we employed theory-based tools to understand the determinants related to residents' perceptions of the risk as well as the micro and macro level factors that motivate residents to adopt preventive actions.

Goals and Objectives

Overarching goal. The overarching goal of this doctoral thesis was to explore radon health risk perception of a resident population in Canada by applying a population health approach and a mix of research methodologies, and thereby, building a body of pragmatic evidence to inform radon health risk prevention strategies in Canada and beyond.

Specific objectives and purposes. The specific objective was to explore the risk perception of the residents of Ottawa-Gatineau areas from a population health perspective by applying both qualitative and quantitative methods.

The purpose of the *initial qualitative pilot study* was to gain insight that can help to design a quantitative survey instrument. The *main qualitative study* aimed to gain a deeper understanding of the aspects of the risk perceptions, along with the exploration of concerns, enablers, barriers of preventive actions, and adaptation approaches taken in response to the risk by the residents in Ottawa-Gatineau. Thus, the evidence collected from the qualitative study used to develop a quantitative survey tool.

The purpose of the *quantitative part* was to determine quantifiable associations and predictions among risk perception variables from a representative sample of residents. The inquiry was to measure independent variables such as radon health risk awareness, perceived susceptibility, severity, and synergistic risk perception with smoking, the smoking situation in homes, care for children, social influence and worldview. The dependent variables included residents' intention to test for radon, actual testing and mitigation of houses for the health risk. The control variables were age, gender, level of education, annual income, occupation, racial or ethnic background and homeownership. Another objective of this inquiry was to examine the macro and micro level social determinants relating to the perception of risk and motivations for preventive actions to whatever extent possible within the target area and population.

Finally, both the *qualitative and quantitative* results were to analyze together to uncover complementing or contradicting evidence to gain a holistic understanding of the social antecedents and determinants relating to the radon health risk issue for the purpose of formulating some useful policy recommendations.

Research Questions

Main research question. How do Ottawa-Gatineau residents ('the residents' hereafter) perceive and act in response to radon health risk?

Qualitative sub-questions. a) How do residents learn about radon and how do they view the risks associated with it? b) What are the enablers and barriers to risk mitigation actions according to residents? c) What suggestions do the residents provide to enhance information dissemination and protective action?

Quantitative sub-questions. a) Is residents' intention to test for radon associated with any of the following variables: Perceived radon health risk susceptibility, severity, the synergistic risk of radon with smoking, smoking in the home, care for children and social influence?

b) How do these variables (mentioned above) predict residents' efficacy in adopting protection behaviours (i.e. testing and mitigation of homes for radon)?

Mixed methods research question. a) How do radon health risk perceptions vary among the residents' sub-groups with the differences in age, gender, education, income, race/ethnicity, and homeownership status? b) What are the social antecedents determining differential radon health risk perception and motivation for preventive health actions?

Final research question. (Considering the application of evidence gathered):

c) What are the policy recommendations based on evidence gathered?

The Hypotheses

First, we assumed that there would be significant associations between perceived radon health risk susceptibility, severity, synergistic risk perception, smoking in the home, and care for children, and social influence with residents' intention to test for radon.

Second, we anticipated that these variables would predict residents' adoption of protective behaviours; however, both the associations and predictions might vary for the population sub-groups considered by age, gender, education, income, race/ethnicity, and homeownership.

Rationale of the Research Project

The justification for undertaking this research project relates to four specific considerations as detailed below:

Lack of Information

Other than a few quantitative studies assessing the environmental health risk perceptions in general, there have been no qualitative or mixed methods studies in Canada to identify and measure residents' perception of radon health risk. Among the identified studies, Krewski et al. (2006) conducted national surveys on health risk perception in 1992 and 2004; and looked into thirty common health hazards. A more focused study by Spiegel and Krewski (2002) evaluated the health risk perception of radon along with three other health hazards affecting residents of high radon areas in Winnipeg, Manitoba. They examined compliance with the radon guideline and concluded that the Canadian Radon Guideline was not effectively prompting homeowners to reduce exposure to radon gas (Spiegel & Krewski, 2002). The study also acknowledged that the public perception of the risk frequently contrasted with the statistical determination of the risk, noting that such differences are not addressable merely by the targeted health communication campaigns (Krewski et al., 2006). Although these studies credibly supported the establishment of the guideline by the federal government, no follow-up study has been conducted to focus on radon health risk perception to support the National Radon Program (NRP) of Health Canada.

Innovations

This study employs a novel methodological approach in a population health issue by mixing quantitative psychometrics with the qualitative exploration of risk determinants to develop a deeper understanding of the radon health risk perception from residents' perspective. The study participants include homeowners as well as tenants – a group that has been excluded from all previous radon studies. The research design facilitates community visits and engagement with residents in conversation to explore factors that keep them from taking preventive actions. Another innovative aspect of the research is the approach of analyzing data using a mixed method design to triangulate the findings from qualitative and quantitative studies.

Implications

Effective risk management strategies are best developed through a deeper understanding of the contextual factors that underpin target populations' beliefs and perceptions about the risk (Nutheam, Harris & Wise, 2010). By identifying the risk determinants, this study generates a systematic and contextualized view of radon-related awareness, perception, and behaviour. The outcomes have implications for targeting interventions to increase actual radon testing. Thus, the study contributes to increasing uptake of the NRP and saving lives from radon-induced lung cancer in Canada and beyond.

Contribution to the Field of Population Health

The analysis of the social determinants relating to the health issue helps to understand the link between risk perception and adaptation behaviours. This opens up the possibility for future research to further explore the health promotion strategies. Identifying the differential distribution of risk among the subgroups of residents, provides valuable information about the social gradient of health. This, in turn, facilitates the achievement of population-wide goals that call for closing the health inequity gaps and improving social justice. Thus, it will contribute to the overall health and well-being of the population in our target areas and beyond.

Background of Radon Health Issue

Historical Perspectives

Radon is a discovery of Canada. In 1899, Ernest Rutherford described radon as the fifth radioactive element after Uranium, Thorium, Radium and Polonium at the McGill University in Montreal (Brenner, 2000; Partington, 1957; Schüttmann, 1988). Although one year earlier, Pierre and Marie Curie had reported on the gas emitted by Radium (Curie & Curie, 1899). However, Ernest and Owens noted a unique phenomenon that radiation from Thorium oxide had random variations, whereas that from Uranium remained remarkably constant (Rutherford & Owens, 1899). Ernest also noticed that Thorium emits a radioactive gas continuously that retains radioactivity for several minutes, and he called the gas 'emanation' (Latin emanae - to elapse and emanatio - expiration) (Rutherford, 1900), but did not patent it as such. However, the history credited Friedrich Ernst Dorn for naming this radioactive gas as ‘radon’ (Ra Em -Radium Emanation) in 1900 AD (Dorn, 1900).

Following the discovery, a wide variety of fields such as meteorology, geophysics, mineral exploration and health sciences studied radon and its progenies extensively and contributed to the scientific literature. Recently, Radon studies go beyond the terrestrial studies given that NASA started generating data about radon and its progeny on the Moon and Mars (Mc Laughlin, 2012). Therapists have been using radon seeds over the century to irradiate malignant tumours. Nevertheless, radon came to the limelight in the 1950s, when a causal association was confirmed in the USA with the increased incidence of lung cancer in underground Uranium miners (Lubin et al., 1995). Since then, public health effects from exposure to radon in residential buildings have increasingly been drawing attention. Wide-ranging epidemiological studies have been covering both underground miners and the general public to quantify lung cancer risks from radon exposure. Based on a body of empirical evidence, the International Agency for Research on Cancer (IARC) classified radon as the category one human carcinogen in 1988, and the World Health Organization recognized radon as the second leading cause of lung cancer globally after smoking in 2009 (WHO, 2009). An IARC review of Group on carcinogens reaffirmed this classification in 2012 (IARC, 2012). Accordingly, various level of governments adopted radon management strategies aimed to prevent radon-induced lung cancer (Laughlin, 2012).

Properties and Toxicology

Radon is a chemically inert gaseous trace element. It originates from bedrock and is ubiquitous in soil and groundwater. The primordial radionuclides of Uranium (^{238}U, ^{235}U) and Thorium (^{232}Th) decay in a series to produce radon gas (Guo, Tian, Wang, Lv, Ma, & Wei, 2016). The most abundant isotope - radon (^{222}Rn) comes from the decay chain of ^{238}U (Figure 1 below). Half-Life of radon is 3.83 days; it passes through an intermediate decay chain to a solid form lead (^{206}Pb). During this process, 50% of it decays to radioactive polonium daughters (i.e., ^{218}Po, ^{214}Po, ^{214}Pb, ^{214}Bi) (Angileri et al., 2018). Radon gas is colourless, tasteless, and odourless and therefore, the human senses do not detect it even at high concentrations (Guo et al., 2016).

The real health hazards come through the further decay of radioactive daughters that emit α and β particles; these have a significantly higher dose effect on health than x-rays or γ-

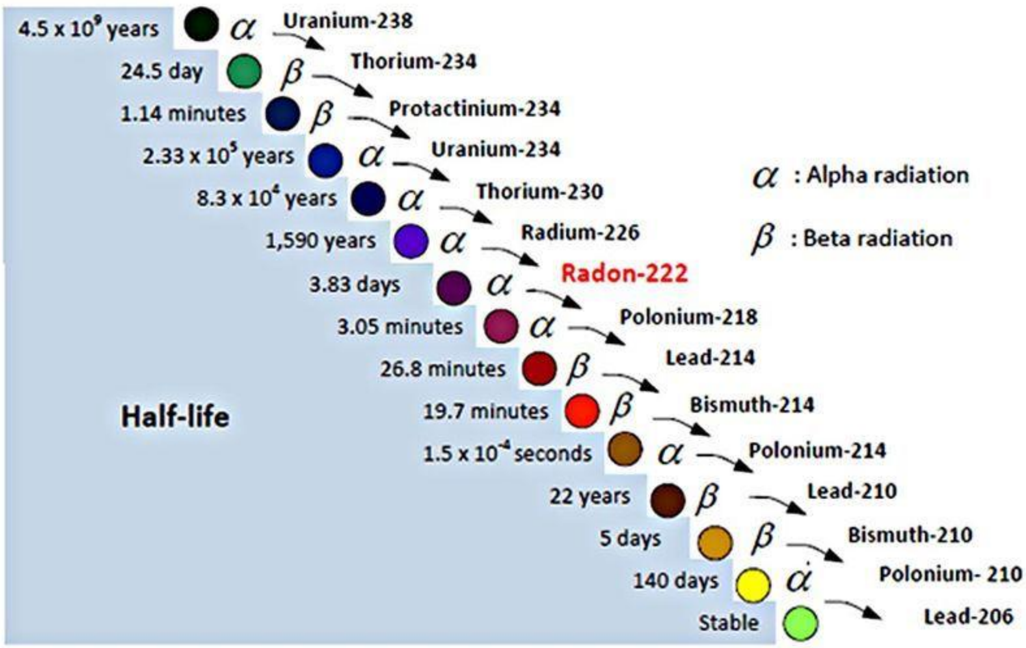

Figure 1. Decay Chain of Uranium^{238}

(Canadian Nuclear Safety Commission, 2012; reproduced with permission).

rays (Little, Kennedy, & McGandy, 1985). These particles bind to dust in the air and are inhaled as solid elements that irradiate lung and bronchial tissues (Marsh & Bailey, 2013).

Alpha particles are the most potent as they carry enough energy to remove electrons from other molecules, leading to ionization. They readily ionize DNA and break it apart as they travel through tissue, generating irreparable DNA damage (ICRP, 2007). DNA damage leads to the genetic mutation that increases cancer risk with each new α-particle emission (Gustavino et al., 2014). An estimate made by the Calgary University scientists revealed that a new radon-induced lung cancer case is adding to the cancer load every single day in Canada (Moore, Stanley, & Goodarzi, 2014).

Radiation is measured in Becquerel (Bq). One Bq is a quantity of radioactive material released from one nucleus decay in one second. Radon concentrations are expressed as Bq/m^3 (per cubic meter of air; IAEA, 2019). As per the United Nations Scientific Committee on the Effects of Atomic Radiation, 100 Bq/m^3 equates to 2.5 mSv/year absorbed radiation by the adult lungs (UNSCEAR, 2000). Health Canada indicates that 200 Bq/m^3 represents the maximum acceptable exposure before certain and severe health risks (Health Canada, 2013). As an example, if on average a person is exposed to 200 Bq/m^3 of radon for one year, it equates to 5mSv/year. Radiobiologists estimate that 50 mSv produces about 1 DNA double-strand break per cell, a genetic-mutation-promoting event capable of shearing entire chromosomes (Goodarzi & Jeggo, 2012). Considering 90% of DNA damage is naturally repaired without genetic error, which compares to 736 million mutations/lung per year in a person inhaling 200 Bq/ m^3 of radon (Stanley et al., 2017). Thus, estimates from the census data from different radon prone regions of Canada indicate that an overall 16% of lung cancer cases are attributable to exposure to radon gas. This estimate is based on the average 6.9% homes of Canada having radon level above 200 Bq/m^3. Hence, the radon-induced lung cancer prevalence will vary according to the percentage of households having radon level above the guideline level in different regions such as in Saskatchewan (9%), Calgary (12.4%) and Manitoba (19%) (Health Canada, 2012, 2013). As per WHO (2009), an increase in dosage of 100 Bq/m^3 raises the lifetime risk of lung cancer by 16%.

Radon Epidemiology

Natural radioactivity is the primary source of human exposure to ionizing radiation. As per the United Nations Scientific Committee on the Effects of Atomic Radiation (2016), 80 % of total human exposure to radiation dose comes from natural sources. There are three primary natural radiation sources - indoor radon, terrestrial radioactivity and cosmic radiation. Although each of these components shows both geographical and temporal variabilities, indoor radon exposure is the most variable and major contributor to most people. (Laughlin, 2015). The natural radioactive gas radon fluctuates with multiple geologic, geographical, gravitational, atmospheric, climatic, seasonal and even diurnal meteorological variabilities (Appleton, 2007; Chen & Marro, 2011; El-Zaher, 2011; Font & Baxieras, 2003; Fro ka, & Jilek, 2014; Henderson et al., 2012; Janssen, 2003; Schubert, Musolff, & Weiss, 2018; Zakhvataev, 2015). Globally, 25% of patients with lung cancer are non-smokers, and most cases of the disease in developed countries are caused directly by inhalation of radon in homes and workplaces (Chen, 2005; Darby et al., 2006; Parkin, Bray, Ferlay, & Pisani, 2005). Anyone aged 65 years or less who chronically inhales radon is at an increased risk for lung cancer in their lifetime, with children and teens most affected as they have a comparatively large lung size and inhale more air compared to adults (Chen et al., 2013; Darby et al., 2005; Henshaw, Eatough, & Richardson, 1990; Krewski et al., 2005; Lubin et al., 1995).

The extrapolation of data from the uranium miners in the USA suggested that residents of high-radon areas are at an increased risk of lung cancer (BEIR VI, 1988). Evidence from a series of studies established the causal link between exposure to radon and lung cancer in human. Among these are a meta-analysis of eight national epidemiological studies (Lubin & Boice, 1997) and case-control studies in the South-West of England (Darby et al., 1998) were the foremost. The collaborative analyses of individual data from thirteen European case-control studies (Darby et al., 2005) and from seven North American studies (Krewski et al., 2005) provided evidence that 5-16% of all lung cancer cases are attributed to the effects of environmental radon gas based on the geographical locations (Groves-Kirkby et al., 2008).

Recent epidemiological findings from residential studies demonstrated a statistically significant increase in lung cancer risk from prolonged exposure to indoor radon at levels above 100 Bq/m^3 (Ciotoli et a., 2017).

In the outdoor environment, radon concentration varies from 5-15 Bq/m^3, and it readily dilutes with ambient air; thus, it can cause no harm (WHO, 2016). Whereas radon concentrations are extremely low in outdoor air, concentrations can become dangerously high indoors due to accumulation in closed spaces. Thus, in the built environment, radon concentrates and breaks down into its daughter progeny. The inhalation of indoor radon progenies contributes to over 50% of the annual dose of ionizing radiation received by an average member of the public (Canadian Nuclear Safety Commission, 2017; UNSCEAR, 2016). Thus, indoor Air Quality (IAQ) in public and residential buildings has become a highly important environmental issue, especially in cold countries and in large, densely populated urban areas.

Moreover, the introduction of millennium engineering in the new building criteria, such as improved thermal insulation to ensure energy efficiency, compounds this problem because it tends to reduce air exchange. On average, people spend about 80 to 90% of their time in confined spaces (i.e. homes, workplaces, schools, care centres etc.), and this percentage rises for children, the elderly, and patients (Setton et al., 2013). This indoor time is much more in cold countries, particularly in Canada. Therefore, for maintaining a healthful indoor environment, it is crucial to reduce the exposure to harmful radon gas, especially for the vulnerable population in cold countries (Ciotoli et al., 2017).

Sources of Indoor Radon

Sources for indoor radon (Figure 2 below) include emission from the surrounding soil (Åkerblom et al., 1984); and rock geology, termed as 'geogenic' radon (Ciotoli et al., 2017; Scheib, Appleton, Miles, & Hodgkinson, 2013; Tollefsen, Cinelli, & De Cort, 2017). Besides, radon gas releases from the building materials (Bossew, 2003; Denman et al., 2006a, 2006b, 2007), degasses from the tap water originated from groundwater such as well or borehole (Smith, & Voutchkov, 2017; Kendall, 2004), and a minor amount comes from the natural gas used for heating and cooking (Dixon, 2001; Mitchell, Griffin, & Casman, 2016).

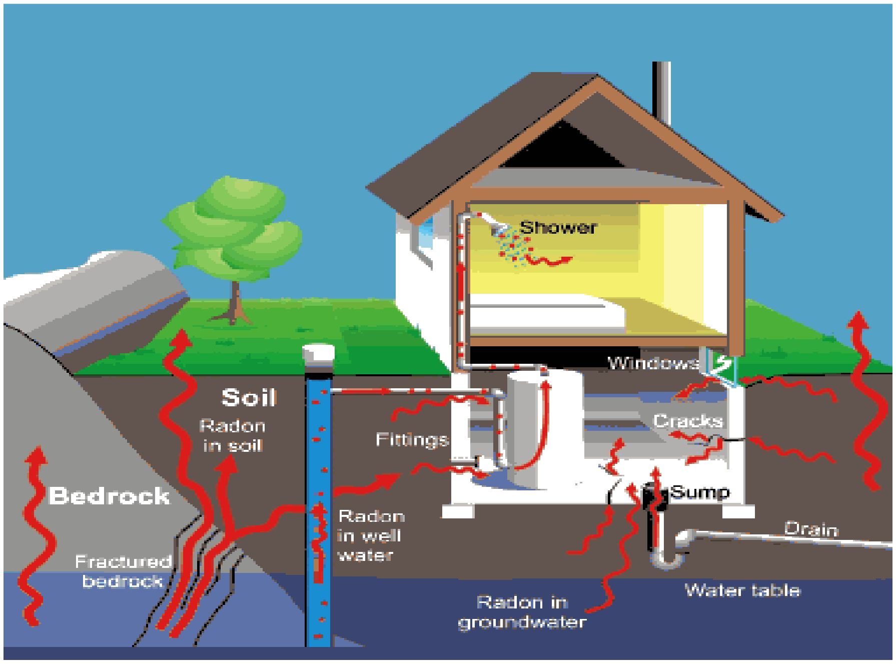

Figure 2. Sources of Indoor Radon

(Reproduced with permission from the Natural Resources of Canada, 2008)

A pressure gradient generated by the effects of wind, indoor-outdoor temperature differences, and ventilation and air-conditioning system causes radon to enter a dwelling from the subsoil, while a diffusion process releases radon from the building materials (Nazaroff & Nero, 1988).

Accumulation of radon is a function of incoming and outgoing ventilation within the building. The dispersion of radon gas from indoor environment is subject to the ventilation rate, commonly expressed in units of air-change per hour, and to a lesser extent, by natural radioactive decay (half-life of alpha progeny, $\tau 1/2 = 3.6$ days). Therefore, the indoor radon concentration is the product of total gains from all sources minus the loss by ventilatory air dilution and natural radioactive decay. Various mathematical models have shown how these complex processes are affected by the variations in the environmental parameters mentioned before as well as changes in the lifestyle of dwellers (Font & Baxieras, 2003; Janssen, 2003).

Building Materials and Radon

Early studies showed an insignificant contribution of radon from the building materials to the indoor environment (Cliff, Green, & Miles, 1985). Gunby, Darby, Miles, Green, & Cox (1993) applied multiple regression on a set of seventeen parameters and showed a significant contribution of radon from specific building materials used in the sidewalls and floors. Compared to the brick walls as a control, concrete walls contributed 20% and stone walls 72% more radon; whereas wooden walls had a 57% reduced rate of radon emission. Thus, the study concluded that building materials could contribute from 20 to 50% of the indoor radon in the U. K. homes (Gunby et al., 1993). The European Commission recognized the fact in 1999. Later studies conducted by Kovler, Perevalov, Levit, Steiner, & Metzger (2005); Kovler, Perevalov, Steiner, & Metzger (2005); Kover (2006) and Jang et al. (2005) marked concrete, coal ash and phosphogypsum plasterboard respectively to be the significant indoor radon contributors, although the use of the latter in the U.K. was controlled since 1972 (O'Riordan et al., 1972).

Paridaens et al. (2005) observed in Belgium that places where overall natural radon emission is low, the indoor radon concentration is augmented by the discharge from the building materials. They found that Belgian houses typically made of clay-brick, mortar, concrete, and wood, had a 20 Bq/m^3 increased level of radon gas. Similarly, Porstendorfer (1994) found about 50 Bq/m^3 more radon in German houses built of construction materials originated from stones. Another study by Ettenhuber et al. (2005) showed that the building materials in Germany exhale from 10-70 $Bq/\ m^3$ of radon to the indoor environment. Likewise, a study in the Netherlands (Stoop et al., 1998) showed that building materials could contribute up to 70% of the national average radon concentration. Studies in Northern Italy (Gallelli et al., 1998) found a higher level of radon in old apartment buildings made up of bricks and stones than in houses built of wooden frameworks. Studies with the high-rise buildings in Hong Kong (Man & Yung, 1999) and Mumbai, India (Shaikh et al., 2003) showed steadily decreased amount of radon with the height from the ground, as air flow rates increase with height. Lastly, Font & Baxieras, (2003) set a dynamic model named 'RAGENA' (radon generation, entry, and accumulation) in the basement of a semi-detached family dwelling near Barcelona, Spain. It showed good agreement with experimental monitoring in approximately one month and confirmed for the specific location that radon release from the construction materials (brick and concrete) could rise to 96.4% of the total concentration. This indoor contribution of radon gas may be the reason behind the residual radon in mitigated houses. This should be a matter of consideration when selecting construction materials as well as radon interventions; because it is already known that radon gas has no threshold level to initiate health harm.

To address considerable public concern about radon release from building materials, a study conducted by the Radiation Protection Bureau, Health Canada, examined radon exhalation rates for 53 different samples of top selling brands drywall, tile and granite available on the Canadian market for interior home decoration obtained from four stores in Ottawa. They found the radon discharge rates ranged from non-detectable to 312 Bq/m^3 per day. Slate tiles and granite slabs had relatively higher radon exhalation rates than other decorative materials, such as ceramic or porcelain tiles. The average radon exhalation rates were 30 Bq/m^3 per day for slate tiles and 42 Bq/m^3 per day for granite slabs of various types and origins. The analysis showed that even if an entire floor was covered with a material having a radon exhalation rate of 300 Bq/m^3 per day, it would contribute only 18 Bq/m^3 to a tightly sealed house with an air exchange rate of 0.3 per hour. Thus, they concluded that building materials used in home decoration make no significant contribution to indoor radon for a house with adequate air exchange (Chen, Rahman, & Atiya, 2010).

Chapter Two: Literature Review

An early scoping review was conducted applying the '*Integrated Population Health Framework*' (Krewski et al., 2007) to examine the effects of a set of determinants on the exposure to radon health risk in different population sub-groups. These determinants ranged from the biology and genetics, environment and occupation to the social and economic factors that influence the health risk of radon. The article was published in the peer-reviewed journal *'Interdisciplinary Journal of Health Sciences'* on March 19, 2017. Text of the article is pasted below. (The article can be read from the journal website clicking this link:

https://doi.org/10.18192/riss-ijhs.v7i1.1872)

Scoping Review Article:

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

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Abstract

Radon is a known carcinogen found in indoor air that exists at higher than the federal reference level (200 Bq/m^3) in about 10% of Canadian homes. Every year, over 3,200 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 800 Bq/m^3 down to 200 Bq/m^3) 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 (NRP).

Keywords: Radon, public health risk, determinants of health, population health principles, interdisciplinary approach.

Résumé

Le radon est un agent cancérigène connu dans l'air intérieur dont la concentration est supérieure au niveau de référence fédéral (200 Bq / m^3) dans environ 10% des foyers canadiens. Chaque année, plus de 3 000 personnes meurent du cancer du poumon provoqué par le radon, qui représente 16% des décès annuels par cancer du poumon au Canada. Le radon est la principale cause de décès par cancer du poumon chez les non-fumeurs et le deuxième chez les fumeurs. Les enfants, les femmes et les fumeurs des groupes à faible revenu sont touchés de manière disproportionnée. Bien que le gouvernement fédéral ait révisé la directive (de 800 à 200 Bq / m^3 précédemment) et que les gouvernements provinciaux aient révisé les codes du bâtiment pour limiter l'exposition, des controverses subsistent quant aux dernières avancées scientifiques dans l'adoption de stratégies de gestion du radon au Canada. Cette revue applique un cadre intégré de santé de la population pour examiner les relations et les interactions entre les déterminants de la santé de la population tels que la biologie et la génétique, l'environnement et la profession, et les facteurs sociaux et économiques qui influent sur le risque du radon pour la santé. Les preuves rassemblées appuient l'analyse des politiques avec l'application de principes d'éthique et de gestion des risques qui conduisent à l'identification de stratégies de prévention efficaces et abordables, à grande échelle et au niveau de la population. Les conclusions finales améliorent le cadre en ajoutant des modalités d'intervention critiques au Programme national sur le radon de Santé Canada.

Mots clés : Radon, risque pour la santé publique, déterminants de la santé, principes de santé de la population, approche interdisciplinaire.

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

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, 2014). The rate of entry is enhanced by a growing negative pressure inside heated homes when the temperature falls outdoors (Fro ka & Jilek, 2014). Radon degrades to emit radioactive alpha particles that attach to indoor aerosols, smoke, and particulate matters (CNSC, 2017). Upon inhalation, these alpha particles can induce DNA mutations in lung tissue, which can lead to cancer (ICRP, 2007).

About 10% of Canadian homes have been identified as containing radon gas exceeding the federal reference level (200 Bq/m^3; Henderson et al., 2012). Over 3,200 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 SES are disproportionately affected (Hill et al., 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 (CELA, 2017; Health Canada, 2014).

In 2007, the Federal Government revised the original 1988 guideline for acceptable levels of radon (lowering it from 800 Bq/m^3 to 200 Bq/m^3), 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. Firstly, the reference level (a cut-off point to minimize risk) is still twice that of the 100 Bq/m^3 recommended by the World Health Organization (2009). Secondly, 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 et al., 2005; Turner et al., 2011).

As per Rose's population strategy of prevention, shifting the distribution of a risk factor to a whole population would 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 the 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 enacting the building codes where radon level is high, are not the best solutions for radon risk management.

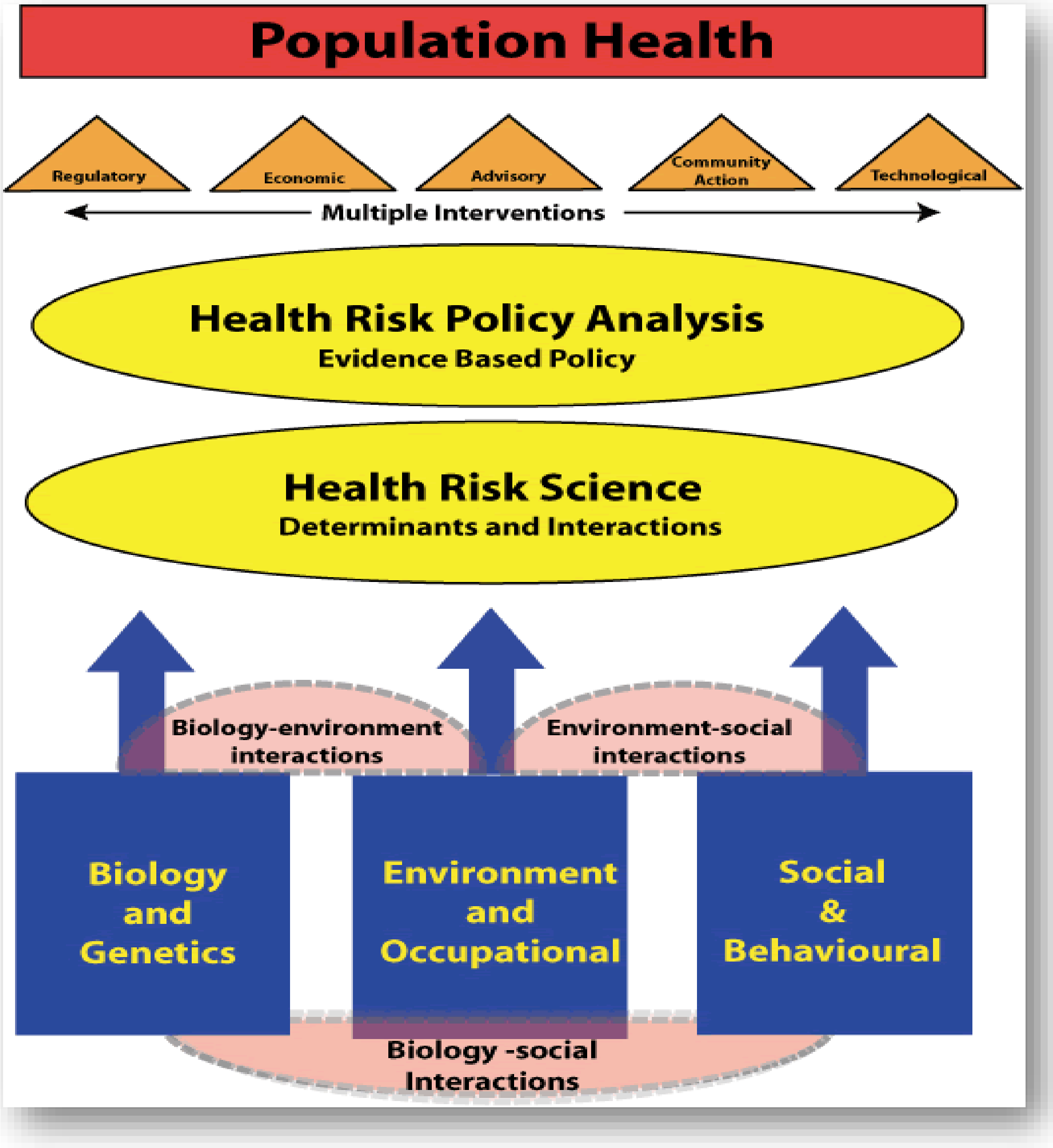

Figure 3. The Integrated Population Health Framework

(Reproduced with permission from Krewski et al., 2007).

For this reason, this review applies an *Integrated Population Health Framework* (Figure 3 above; 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.

Integrated Population Health Risk Assessment and Management Framework

The framework is based on three basic sets of population health determinants: a) biology and genetic endowment, b) environment and occupation, and c) social and behavioral factors. This review synthesized 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 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,” “heath disparity,” and “health equity.” Reference lists of identified articles were also searched for

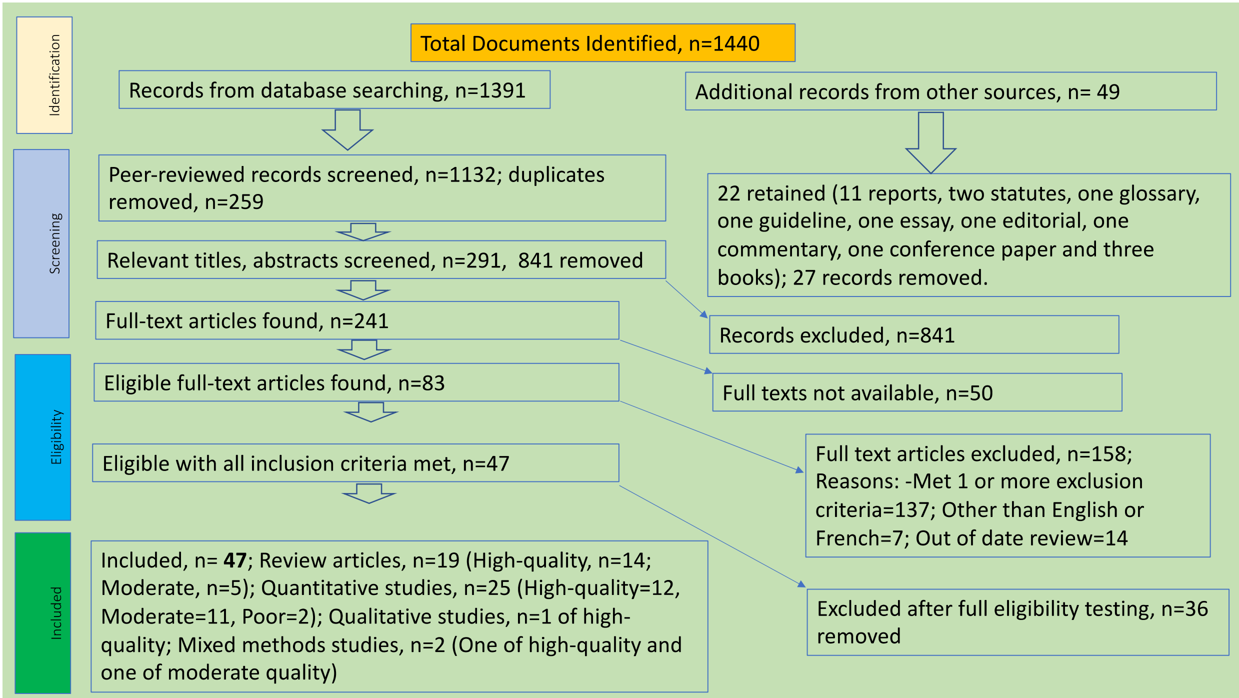

Figure 4. PRISMA Flow Diagram: Scoping Review

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 the World Health Organization.

Search results. A total of 1,440 documents were identified (Figure 4 above); 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 qualities, five moderate qualities (AMSTAR criteria)], and 25 were quantitative studies [12 high quality (experimental), 11 average (case-control and 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. There were 11 reports, two statutes, one glossary, one guideline, one essay, one editorial, one commentary, one conference paper, and three books also included -these minimized 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:

Biology and genetic endowment. Feeble biological construction (Chauhan et al., 2012; Robertson et al., 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, would 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.

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 (Fro ka & Jilek, 2014). Therefore, increasing airtightness of dwellings in pursuit of energy efficiency would increase radon emission from the ground (Vardoulakis et al., 2015). Exposure would 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, Richard, Deutsch, Benmarhnia, Pirard, Roudier, et al., 2013; Poortinga et al., 2011).

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 et al., 1994), increasing life-years lost threefold compared to never-smokers (Noh et al., 2016).

Interactions between the Determinants

Gene and 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.

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).

Biology and 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 would have more dust, aerosols, combustion by-products, and tobacco smoke, which would mix with radon decay products (RDP) to get fixed in lung mucosa that is already irritated by tobacco smoking (Schmid et al., 2010).

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).

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 (Briggs et al., 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) find 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; yet according to a Canadian survey, there has been a significant rise in lung cancer risk due to residential level exposure (Statistics Canada, 2015).

The level of awareness about the risk is critical to scaling up the preventive programs (Beck, Richard, Deutsch, Benmarhnia, Pirard, Roudier, 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 et al., 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/m^3, but once they were made aware of the health risks, they became willing to pay for remediation even at a level of 702 Bq/m^3 (Spiegel & Krewski, 2002).

As per the above evidence, radon exposure is a serious public health problem. People adopt testing and remediation measures reluctantly even when they are aware of the risk.

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 et al., 2015; Hystad et al., 2014).

Discussion and Health Risk 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, 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, 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 would 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: a) Adopt a fair process of decision-making that is unbiased and objectively covers all vulnerable dwellings as far as possible. b) Use the limited risk management resources optimally to maximize benefit. c) Ethical principle of autonomy requires that residents should be provided with the necessary information and they should be involved in decision-making. d) Be flexible and evolutionary to accept new scientific evidence. e) Be aware that complete elimination of radon risk is not possible even after employing all efforts (Barrett, Stiles, & Patterson, 2012).

Radon Health Risk Management: Multiple Interventions

Drawing on the evidence synthesized above, 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:

Regulatory action. Many European countries have introduced regulations to protect their populations from the risk of lung cancer associated with radon exposure (Bochicchio, 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 (Dunn & Cooper, 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.

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.

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. There could be an inspectorate within Health Canada to randomly inspect susceptible houses, test for radon, and advice on remediation.

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.

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).

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 advocates, media, as well as individual residents. 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, there have been inadequate media coverage; thus, these communication efforts have not made a significant impact (Nicol, Ryan, & Okocha, 2014). 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, protection motivation 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).

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). The Table 1 below displays messages, activities, and strategies targeting low-income families that can increase radon program uptake:

Table 1. Preventive Actions

(Modified with permission from Larsson, 2014)

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, gym and play areas.
Talk to the Landlord	If renting, talk to the landlord or property manager about measuring the indoor radon level.
Ask Homeowners	Ask homeowners whether the home is tested by a radon professional every three years.
See Results	Ask to see results of radon measurements for children's schools and day-care facilities.
Quit Smoking	Radon higher than the guideline level; one more reason to quit!
Risks and Rewards	Weight having home-gym equipment in a high-radon basement.
Plan Saving	Cannot afford mitigation right away, make a saving plan; your lungs are worth it!
Clean Your Air	Place a surgical mask over the desktop fan.
Shun Wood Furnace	No wood for heating, instead buy a portable air cleaner in installment
Open Doors-Windows	whenever the weather allows
Employ your Furnace	High-efficiency filters block radon particles.
Run a Fan	With an electronic motor with a low-speed setting, running a fan can 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 Videos**

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 demonstrates a need for multilevel interventions. It identifies what is known so far, what works, and what is not consistent with the latest scientific developments.

Finally, it 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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Focused Literature Review

The initial scoping literature review synthesized broader evidence on the relationships and interactions among the determinants that shape exposure to the radon population health risk. It identified the gaps between the latest scientific development and current strategies in radon health risk management in Canada. It also recognized the need to explore people's psychometrics that includes the facets of the risk, risk perception and worldviews that could help understand the motivation or demotivation for action. These helped to narrow down the focus on literature related to the topic of this project. Therefore, the purpose of this summary review was to concentrate on the specific aspects of radon health risk perception from the peer-reviewed literature to be able to formulate tools that would facilitate designing the research questions. This review looked deeper into the diverse facets that could be related to the risk as it is perceived, analyzed, and managed by residents depending on their contextual situations.

Radon Health Risk Perception

While an epidemiological stance refers to risk as the quantitative measures of the probability of experiencing some adverse health outcomes, a psychological perspective is far more complex and nuanced (Hevey, 2017). Here, risk perception encompasses people's beliefs, attitudes, judgments, and feelings that relate to the broader social and cultural tenets, and approaches they adopt in managing the risk (Pidgeon, 1992). This viewpoint emphasizes the innate multi-faceted aspects (cognitive and emotional) of risk perception and context-specific aspects (personal, familial, communal, sociocultural) relating to the risk management (Slovic, Finucane, Peters, & MacGregor, 2004).

Research has noted that the intention to test for radon is associated with the perception of reality of the hazard and urgency of the threat (Weinstein, Sandman, & Robert, 1991). Similarly, individual awareness about the susceptibility and severity of the risk together with the prevailing community concerns determine risk management behaviours (Weinstein et al., 1991). In light of the above, an analysis of radon health risk perception is presented under the following sub-headings:

Unique Nature of Radon Health Risk

The key challenge to radon health risk communication relates to the fact that this risk is perceived to be too low or simply non-existent (Doyle, McClelland, Schulze, Locke, & Elliott, 1990; Fisher, McClelland, Schulze, & Doyle, 1991). Radon is a naturally occurring hazard without any immediacy or urgency in its effect, and this is the primary factor discouraging people from taking any preventive action. As a colourless, odourless, and tasteless gas, radon has no sensory cues; thus, raises no alert that could bring people to seek any protective support (McKenzie-Mohr, 2000). Adding to the underestimation of the seriousness of the risk is its silent effect; the exposure to radon develops no signs, and there are no early symptoms that can bring a victim to the physician (Hevey, 2017). The risk is neither technological that people usually perceive to be dangerous (Sandman, 1987); nor is it associated with any industrial process that may warrant public outrage and call for immediate government actions (Hevey, 2017). Another aspect is its long lag period extending over decades before manifesting any effect and a myth that any harm can be fixed later (Smith, 2001). Thus, a low level of perceived risk leads people to consider it too insignificant to be flagged for action (Kahneman & Tversky, 1979); and the cumulative effect of these factors discourages people from taking preventive measures.

Cognitive and Affective Risk Perceptions

Contemporary theories in cognitive psychology and neuroscience stipulate that there are two basic processes of risk perception – cognitive and affective (Slovic, Finucane, Peters, & MacGregor, 2004). The cognitive risk perception applies analytic systems, algorithms and normative rules, such as probability calculus, risk assessment and formal logic. It is relatively effort intensive, slow and requires conscious control. On the other hand, the affective risk perception employs experiential systems that are intuitive, fast and spontaneous but not always calculated with conscious awareness. As per Slovic et al., (2004), while the first form of risk perception follows modern scientific analysis, the latter follows primitive human instincts and intuitive reaction that helped humans survive throughout the history of evolution and exists till date as the most common and most natural way to respond to any form of risk. It relies on images and associations that link experience to emotion and affect. Besides, these two types of risk perception, Slovic (2001) has described a third perception of 'risk as politics'. It relates mainly to decision making and policy formulation and is dealt with in a latter section of this thesis.

Proponents of cognitive risk perception tend to consider affective risk perception irrational. However, real-world experience disagrees with this argument. A large body of scholarship on risk analysis has demonstrated that the rational and experiential systems act in parallel, and one relies on the other for guidance (Isen, 1993; Johnson & Tversky, 1983; Kahneman $ Snell, 1990; Loewenstein et al., 2001; Mellers et al., 1997; Wilson et al., 1993; Zajonc, 1980). The emotional aspect of risk perception has been found to drive individuals' motivation for action. (Tversky & Kahneman, 1981). We intended to explore this aspect of interdependence in this thesis.

Risk Response Heuristics

We assume that health communications campaigns in Canada are focusing mostly on the cognitive aspects assuming that people would act rationally once they get the information. Psychological theories and research illustrate intricate pictures through some well-founded heuristics on how people actually respond and what may inhibit appropriate behavioural responses to the risk information (Tversky & Kahneman, 1974; Tversky & Kahneman, 1981; Witte, 1992). A brief description of some of these heuristics follows:

Availability. If there is a similar past event or image that one can recall; for example, some non-smoker develops lung cancer, it can be speculated to be due to the exposure to radon. While the presence of such a case becomes the basis for judging the likelihood of developing similar lung cancer, the absence can lead people to ignore the risk (Hevey, 2017).

Representativeness. The proposition that people gain from experiential knowledge. For example, smoking history or living near a nuclear power plant represents the premise of lung cancer but merely being in one's own home does not fit this ground. It is the basis for denial of any risk from residential radon (Hevey, 2017).

Unrealistic optimism. This is similar to optimistic bias. As an example, in the US, people who did not test radon in high-risk areas were hopeful that radon would not harm them (Klotz, & Sandman, 1988). Similar unrealistic optimism was noticed among residents of high radon areas in Ireland as they believed radon to be a threat to others in the community but not for them (Clifford, Hevey, & Menzies, 2012).

Emotional response to the active agency. Research has shown that individuals feel more threatened by the description that portrays radon as an active agent rather than passive (Dragojevic, Bell, & McGlone, 2014). For example, when it is told that 'radon gas invades your homes' people are alarmed and feel more insecure than just telling that 'radon gas seeps into homes.' As there is an emotional attachment with homes, it is difficult to accept that this physical and psychological place of safety can be a threat to health (Hevey, 2017). In this study, we want to explore how analytic reasoning translates to action when influenced by the intuitive affect.

Contexts of Radon Health Risk

Personal experience informs risk perception in a given context including interpersonal networks and social backgrounds (Maibach, Roser-Renouf, & Leiserowitz, 2008). The community norms further influence this and give it a wider frame, consideration, and agenda for action. Thus, risk perception is a shared and collective experience as people seek information and guidance from their social networks and trusted sources (Hevey, 2017). For radon, there is still no broader community action built through consensus, and therefore, people do not take it as a threat. Whereas such established social movement (such as anti-war, animal rights, environmental protection) motivates people to come out and raise their voice for taking action. Lack of the same is evident for radon even in high radon areas (Wang, Ju, Stark, & Teresi, 2000). Thus, we assumed that unlike any other public health issues, radon risk perception would intricately correlate with some personal, interpersonal and social characteristics.

Determinants Affecting Radon Risk Behaviors

The factors identified in literature to have a positive correlation with radon testing and remediation behaviors are education (Wang, Ju, Stark, & Teresi, 2000), income (Halpern & Warner,1994; Hill, Butterfield, & Larsson, 2006), female gender (Halpern & Warner,1994), children living in a household (DiPofi, LaTour, & Henthorne, 2001), home ownership (Hampson, Andrews, Lee, Lichtenstein, & Barckley, 2000), and younger age (Halpern &

Warner,1994; Wang, Ju, Stark, & Teresi, 2000). Perception of synergistic risk from the combined exposure to radon and tobacco is also a motivation for testing (Hampson, Andrews, Lee, Lichtenstein, & Barckley, 2000; Lichtenstein, Boles, & Lee, 2008). Previously, it was noted that despite increased risk, smokers are less concerned about radon than non-smokers (Kennedy, Probart, & Dorman, 1991; Mainous & Hagen, 1993). However, a latter study found that current smokers are six times more likely to plan for the test than non-smokers (Hahn, 2014). Living in high radon zones is inconsistently associated with the intentions to test and remediate (Clifford, Hevey, & Menzies, 2012; Duckworth, Frank-Stromborg, Oleckno, Duffy, & Burns, 2002).

Worldviews versus Risk Perception

Worldviews are the general social, cultural, and political attitudes held by citizens that impact their judgments about complex issues (Slovic, 1999). As per Dake (1991) worldviews are some 'orienting dispositions,' that guide people's responses to the risk. To date, a group of worldviews have been identified and measured. The following are a set of worldviews with example statements representing peoples' attitude towards risk as mentioned by Slovic (1999): a) ***Hierarchic:*** Hierarchists like a top-down administered society where commands flow down from the authorities and obedience flows up to the hierarchy. (e.g., Experts should take the final health decision). b) ***Individualism:*** Such people prefer to do their own business without any interruption from the government or any other controls (e.g., It is fair for individual with more ability to earn more). c) ***Egalitarianism***: They like a world where powers and means are distributed equally. (e.g., all should be treated equally to have less problem). d) ***Technological Enthusiasm*****:** People think in advance and desire to stay abreast of the latest development of science and technology and want to get the best out of the latest innovation (e.g., An advanced technology awareness is crucial to improving health and social well-being). We plan to explore what types of worldviews our residents' hold regarding radon health risk in their houses (Slovic, 1999).

Conclusion of the Literature Reviews

After the initial scoping review, the variables and constructs were generally identified but were not adequately backed by relevant literature that studied the specific tenets of risk perception. We came to know that while the comprehensive multi-media health communication programs show success in raising public awareness (cognitive) of radon, there is a consistently low effect on taking actual protective actions (Dowdall, Fenton, & Rafferty, 2016; Doyle, McClelland, Schulze, Locke, & Elliott, 1991; Zhang, Chow, Meara, & Green, 2011). In Canada, like many other countries, individuals are responsible for radon testing and remediation. The federal guideline on radon is voluntary, and the role of government is to assess the risk, determine the efficacy of remediation strategies, and support public awareness campaigns. Such an approach is based on the best assumption that residents would act rationally following the information provided. However, psychological and social science research has shown that there are multiple steps required for an individual on the way to translating information into rational behaviours (Hevey, 2017). The sequences theoretically predict the responses to health threat information people will take to the best interest of their health although such an assumption neither fits with the real-life scenario, nor with the psychological aspect of risk perception and behavioural aspect of risk-mitigation as described above (Maziak & Ward, 2009). From this standpoint, a key theme of this project was to explore how people perceive the risk, respond to the health risk information and what factors determine residents' preventive action or failure to taking action in response to the health risk. This focused literature review provides the background knowledge-base from where the research questions as well as the variable and constructs to be measured in this project took shape. These are presented in the Appendix 2.

My Positionality and Reflexivity

As a medical professional, homeowner and resident of the Ottawa-Gatineau CMA, and father of three children who play table tennis in the basement, I am aware of the health risks and of my responsibility. However, I lack knowledge of the perceptions of other individuals who are in similar or different positions than mine. Hence, throughout the study, I maintained an objective stance, attempting to learn from participants what their own views were.

The survey instrument that I used was developed from insight got from a prior qualitative pilot study and validated by the focal persons in Health Canada. In the interviews that I conducted, I did not pose any leading questions to participants, neither did I judge them. I also did not express agreement or disagreement with their points of view. I maintained a neutral stance throughout the various stages of the study, reminding myself that the purpose was to understand participants’ point of view.

Chapter Three: Conceptual and Theoretical Frameworks

While the initial scoping review indicated us to adopt a population health approach, the focused literature review guided us to select the conceptual and theoretical frameworks that would be conducive to achieving the objectives of the project. Below is an outline of our adopted approach, the conceptual and theoretical frameworks at a glance (Figure 5 below).

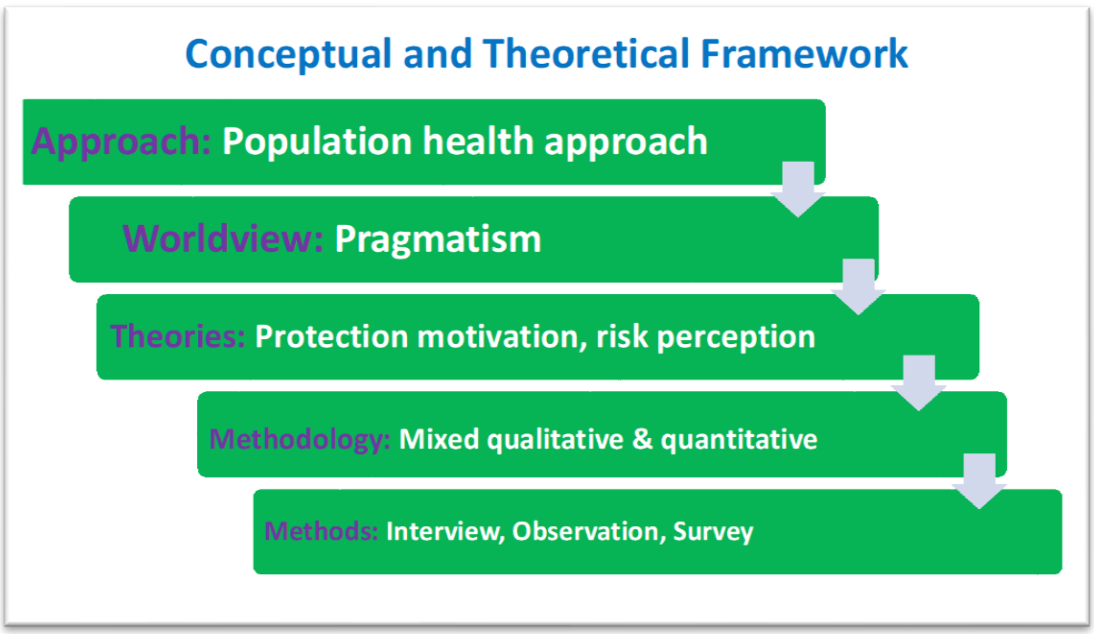

Figure 5. Conceptual and Theoretical Framework

Population Health Approach and Applications

How is Population Health Defined?

As per Kindig and Stoddart (2003), population health consists of "the health outcomes of a group of individuals, including the distribution of such outcomes within the group" (p.381).

Although most often ‘group’ means a geographic population such as a community or a nation, it can refer to a group of employees, ethnic entity, persons with disability, people in long-term care, or any such defined group. The concern for both public and private policymakers is the health outcomes of such groups.

They argue that the field of population health must emphasize the concept and measurement of health outcomes because these draw the research focus on the impact of the determinants of health and their interactions with one another over the life course to produce the health outcomes (dependent variables, Figure 6 below). They also believe that this approach would help determine the distribution of health outcomes among population subgroups; thus, explain health inequality among population sub-groups. They maintain that these relate to underlying ethical considerations that drive policies and interventions both at the individual and social levels to optimize health determinants or factors (independent variables, Figure 6 below). Finally, they make clear the goals of population health, which are to maintain and improve the overall health of a population and reduce health inequities among population sub-groups (Kindig et al., 2003; Kindig, 2007).

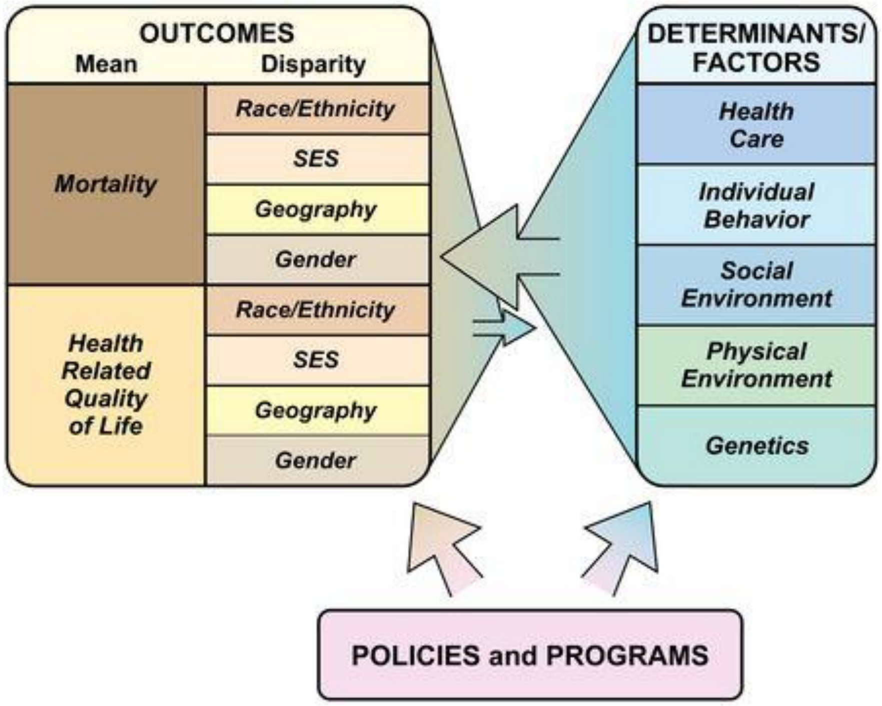

Figure 6. A Schematic Definition of Population Health

(Kindig & Stoddart, 2003; developed version of Figure 6 got through personal communication and reproduced with permission)

An essential aspect of the definition is that population health does not only mean the overall health of a population; however, it goes beyond to involve the patterns of distribution of health among the population subgroups. In one side, the overall health could be reasonably high if more people are quite healthy compared to some factions of the population having ill health. Typically, such inequality can be removed or at least significantly reduced.

The right-hand side of Figure 6 above mentions some health determinants or factors, such as health care systems, individual behaviour, social environment, physical environment, genetics etc. Every determinant affects, and all these have a combined impact on health outcomes of individual and population. The outcomes vary in population subgroups with sociodemographic, economic, environmental and other variances to determine differential rates of morbidity and mortality; thus, produce a varied health-related quality of life (Kindig & Stoddart, 2003).

Population Health as an Approach

Population health is an approach that encompasses the broadest aspect of human health aiming to improve the overall health status of the whole population by reducing health inequities among the population sub-groups. For achieving these objectives, the population health approach covers and acts upon the full range of determinants and conditions that contribute to the health of population. The determinants of health are the broad range of personal, familial, occupational, social, organizational, economic and environmental factors that impact individual and population health. In 1998 the World Health Organization in Europe (Wilkinson & Marmot, 1998) first identified ten factors as the key social determinants of health and major contributors to unequal health outcomes in populations. These are social gradient, stress, early life, social exclusion, work, unemployment, social support, addiction, food and transport.

As per Health Canada (2018), some of the main determinants of health include: Biology and genetics, childhood experiences, education and literacy, employment and working conditions, income and social status, housing stability, physical environments, social supports and coping skills, lifestyle behaviours, access to health services, gender and culture. Among the determinants of health, there is a specific group relating to the social and economic aspects, often called social determinants of health. These pertain to an individual's place in society, such as education, employment and income. Experiences of racism, discrimination or trauma can also be critical social determinants of health for certain groups, including Indigenous peoples and racialized communities in Canada. Addressing social determinants of health means generating changes in the systems which in turn, can support healthy behaviours conducive to positive health and well-being (Health Canada, 2018).

What Does Population Health Do?

As an approach, population health examines the interactions between the underlying determinants and conditions that shape and maintain the health of the population over the entire life-cycle. It systematically investigates the patterns that influence health and applies the outcomes to develop policies and design interventions to enhance the health and well-being of the entire population. The population health approach concedes that health is a capacity or resource rather than a transient state, a characterization which corresponds more to the concept of being able to pursue one's goals, acquire skills and education, and grow. This broader idea of health recognizes the range of social, economic and physical environmental dynamics that contribute to health. The best expression of this notion of health is the capacity to adapt and thrive by successfully responding and controlling challenges that come across the life course (Frankish et al., 2001).

Does Population Health Encompass Everything?

The definition of population health has been critiqued to be too broad as it deems covering everything; therefore, such a concept is not much practical to guide precise research and policy. Nonetheless, Kindig (2007) argued that none from the public or private sectors taking the responsibility to improve the overall health of the population. It is customary for a specific policymaker to care for only one sector or industry. Likewise, each advocacy group also concentrate on a particular risk factor or disease. The intrinsic value of a population health concept is to advance the integration of knowledge from multiple disciplines across and explore the impacts of various determinants on a health issue. Therefore, population health researcher can focus on a single risk factor, measure outcome and its distribution, and design specific policy direction. However, this would be only a part of the whole (Kindig, 2007).

Difference between Population Health and Public Health

The difference between public health and population health is sometimes contentious; thus, it needs attention. Conventionally, people consider public health as a group of essential health functions delivered by the government. For example, preventive vaccines, detecting and controlling epidemics, managing environmental hazards, and encouraging healthy behaviours (Kindig, n.d.). However, this limited governmental view was overcome by the extended definition proposed by the Institute of Medicine (2002) in its report, 'The Future of the Public's Health in the 21st Century'. The report acknowledged that the health of individuals, as well as populations, is determined by a group of determinants relate to the social, economic, natural, built, and political environments. Therefore, it called for adopting a focus on population health that includes multiple determinants of health. It continued emphasizing to develop systems of accountability, based on evidence, improve communication and build innovative intersectoral partnerships by drawing on the perspectives and resources of diverse communities and to actively engage them in health action (IOM, 2002). In reality, no governmental public health agency has such a broad mandate to assure the overall health of the population. The prime reason is that the significant population health determinants like health care, education, and income remain outside public health authority and responsibility. Similarly, the current state of affair provides limited support for the traditional stand-alone emergent public health functions. Instead, a range of sectors and disciplines are involved in discharging services to ensure the health of the population. Therefore, although public health is defined as the health of the public, there remains a distinct difference from the population health (Kindig, n.d.).

Objectives and Goals of Population Health Approach

According to the Public Health Agency of Canada (2012), population health objectives and actions are directed to the health of an entire community, or sub-groups, rather than individuals. Such efforts aim to reduce the inequalities in health status between population sub-groups. A fundamental assumption of a population health approach is that reductions in health inequities require reductions in material and social inequity. The goals of a population health approach, therefore, extend beyond the improvement of population health outcomes to encompass the vision to develop a sustainable and integrated health system, increase national growth and productivity, and strengthen social cohesion and citizen engagement through pro-equity policies and programs. Therefore, population health approach encourages vulnerable citizens' participation in research targeted to improve their health. Thus, it grants opportunities to express their opinion in developing the strategies and setting the priorities for health (PHAC, 2012). Consequently, public trust and confidence develop for research outcomes help secure support for the implementation of population health interventions aimed to achieve the desired health objectives (PHAC, 2012).

In light of the above, the initial scoping review of radon literature concentrated on the impact of a group of determinants and their interactions with one another that affect the differential distribution of radon health risk and identified its population health impacts by employing the 'Population Health Framework.' According to the Household and the Environment Survey 2015, although 55% of residents heard about the radon health risk, only 6%

of them have taken some action to mitigate the risk. The gap between risk awareness and actual preventive actions taken presents a challenge for public health professionals (Nicol, Rideout, Barn, Ma, & Kosatsky, 2015). Thus, we became curious to explore why there is a gap between risk awareness and actual preventive action taken by residents. Therefore, we quantitatively examined the psychometrics of radon health risk perception of a well-defined population of the national capital region- Ottawa-Gatineau areas. This gave us information that the perception of the risk has two dimensions- cognitive and affective. Those who took action for radon mitigation perceived the risk both cognitively and affectively.

Consequently, we kept into consideration the broader population health approach and planned to explore the determinants that could explain the dual risk perception process and provide us with a holistic picture of radon health risk perception. Thus, we conducted a qualitative study intending to examine the determinants that could be targeted as the leverage points for interventions. Later, we identified the most effective radon mitigation interventions and strategies along with the factors worthy of consideration while installing such a system to remediate radon. We did a mixed methods analysis to corroborate and compare the findings gathered through different methods. Finally, we used our compiled evidence to design radon policy recommendations integrating the latest scientific development, policy updates, ethical and risk science issues.

The same population health perspective guided our conclusion that the distribution of the risk should be altered through the pro-equity policy and community-based interventions so that maximum benefits are obtained with the minimum available resources; and thereby, the population health goals are achieved.

Worldview and Theoretical Framework

Worldview: Pragmatic

Pragmatism is a problem-oriented philosophy that acknowledges the importance of the strategic application of research methods to find out the most useful answer to a research question. This paradigm advocates the use of mixed methods in research and "sidesteps the contentious issues of truth and reality" (Feilzer 2010, p. 8). Instead, it focuses on 'what works' and considers that as the reality concerning the research questions under scrutiny (Tashakkori & Teddlie 2003, p. 713).

In a population health approach, this project aimed to explore the determinants and outcomes of radon health risk applying a mix of methods and integrating theories from multiple disciplines to look for empirical evidence with a pragmatic worldview. The population health approach as described above is based on the assumption that interrelated conditions and determinants impact health throughout the life course, and there is a systematic pattern through which these impacts occur and are perceived (Kindig & Stoddart, 2003). This approach is in accord with the pragmatic philosophical worldview that employs diverse and systematic ways to find how things happen, what works and what does not, by giving importance to the research question and valuing both the objective and subjective knowledge (Creswell et al., 2011).

This study draws upon the constructs of epidemiological, psychological, and health promotion theories. The initial literature review (Khan & James, 2017) based on the '*Integrated Population Health Risk Assessment and Management Framework*' (Krewski et al., 2007) demonstrated how a set of determinants interacting among them could affect indoor air quality; and thus, clarified the concepts and variables worth considering for this study. Therefore, a mix of quantitative and qualitative methodologies was adopted to design the investigative tools to collect assorted data. We assumed that analyzing those data generated by mixed methods would allow a holistic interpretation of the outcomes of the study.

Theoretical Lens: Protection Motivation Theory

Theoretically, exposure to a health risk communication initiates two appraisal processes: a) threat appraisal and b) coping appraisal (Witte, 1992).

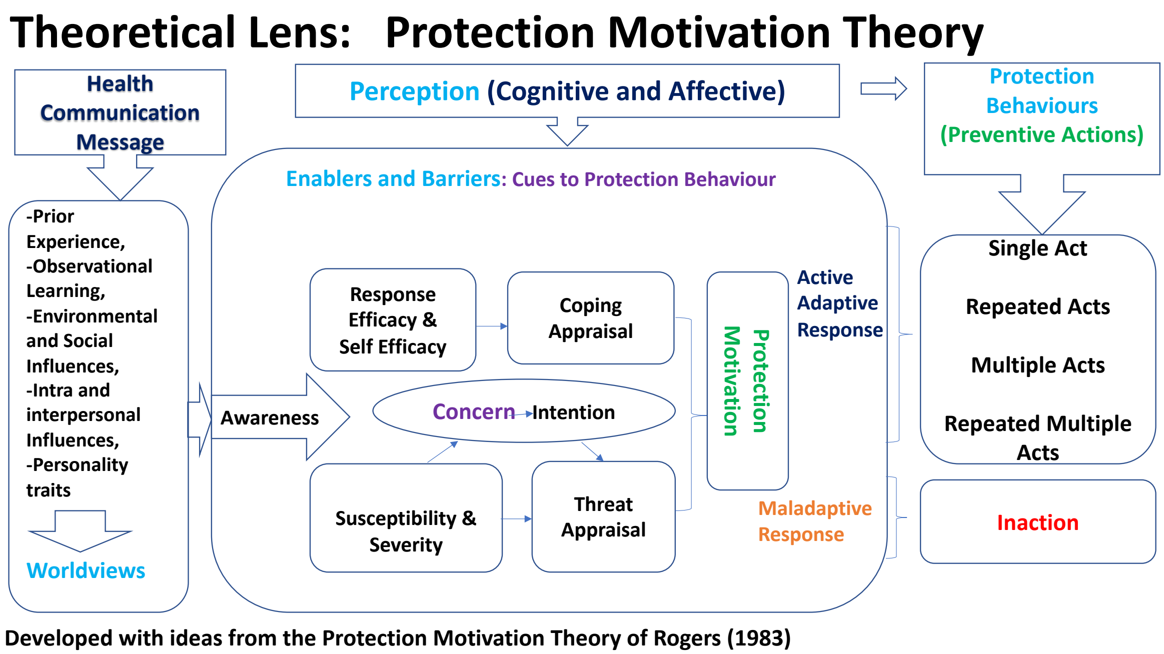

Figure 7. Theoretical lens: Protection Motivation Theory

(Developed with copyright clearance, Rogers, 1983)

Threat appraisal is the assessment of the chance of contracting a disease (susceptibility) and evaluating its seriousness (Severity). A coping appraisal involves response efficacy and self-efficacy. Response efficacy is the expectation that carrying out recommendations would eliminate the threat effectively. Self-efficacy is one's belief in the personal ability to execute the recommended courses of action successfully (Witte, 1992). Accordingly, the more individuals believe they are susceptible to a serious threat, the more they would engage in the coping appraisal. These comprehensions, in turn, determine the intention and ultimately the behaviour of a person that is termed protection motivation (Boer & Seydel, 1996). Thus, the Protection Motivation Theory (PMT) specifies how these two perception processes lead an individual to either adopt an active adaptive or maladaptive coping mechanism in response to health risk (Maddux & Rogers, 1983; Rogers, 1983). The maladaptive responses are those that place an individual at additional risk including behaviours that lead to the negative consequences (e.g. smoking) and end up with inaction. These eventually result in adverse health outcomes (e.g. not testing for radon and thus, missing the opportunity to prevent lung cancer).

Hence, protection motivation has four dynamics: a) perceived probability of the occurrence or vulnerability (susceptibility of getting lung cancer). b) Perceived severity of a threatening event (lung cancer). c) Response efficacy of the recommended preventive behaviour (perceived efficiency of the test and mitigation measures to eliminate the threat). d) self-efficacy (individual's confidence of the capacity to undertake a recommended actions). Thus, protection motivation is the result of an informed threat appraisal and coping appraisal, and as a mediating variable, it stimulates, guides and sustains the protective health behaviour (Boer & Seydel, 1996).

From an initial pilot qualitative study, we identified some 'maladaptive coping behaviours,' that needed more in-depth exploration to understand the conscious adaptive process. Therefore, we assumed that appraising homeowners' perceptions within the above fundamental logics of PMT would help to enhance understanding of the motivation dynamics, thus, discover ways to influence protection behaviours. Consequently, this study aimed to examine the tenets of PMT in a Canadian context to provide some essential theory-based insights regarding homeowners' reactions or lack thereof relating to the health risk of radon.

In health sciences, PMT is applied to influence and predict various health-related behaviours. The key applications have been in reducing alcohol consumption, enhancing healthy lifestyles, improving diagnostic health behaviours, and preventing diseases (Boer & Seydel, 1996). We assumed that a thorough understanding of homeowners' perception would advance the PMT research agenda to promote health awareness, establish a new line of thinking for policy makers and professionals to address the issue in question.

Chapter Four: Methodology and Methods

The above population health approach, pragmatic worldview and PMT theoretical frameworks guided us to define the appropriate methodologies and methods. Thereby, a thesis proposal was developed, submitted and defended on September 14th, 2017. This chapter defines and justifies the methodologies used and elaborates on the methods.

Mixed Methodology

We adopted a mixed methodology that is harmonious with the population health approach and pragmatic worldview and conducive to the achievement of goals and objectives of this project. As per convention, we defined mixed methods research for this project as an approach that focuses on research questions and seeks to understand multi-level influences on radon health risk perception in a Canadian context by employing different perspectives and methods (Creswell et al., 2011). We assumed that while the qualitative research would explore the deeper subjective meanings of the risk, the quantitative analysis would assess the objective magnitude of the variables by purposefully integrating the methods and drawing on the strengths of each separately.

Justification of Using a Mixed Methodology

The reason for selecting this approach was to answer the broad research questions that could not be answered either by quantitative or qualitative method alone. The relevance of using such methods was that radon health risk is unique as described above and there is a set of determinants interacting with each other in different ways that are hard to measure with a single method. Both methods have their strengths and limitations, but we assumed that the combined outcomes would provide us with a holistic picture of risk perception, and the understanding of which would be useful for policy directions and designing programs to address the health issue.

There are examples of approaches that mix methods in health research such as focus group discussions and interviews used to gather insight to design a survey instrument or to identify the relevant variables for a subsequent study (Barbour, 1993). Likewise, qualitative methods are used to develop quantitative research tools or to refine it substantially. In other instances, qualitative work follows a large-scale survey to explore the mechanisms in further details and to see where the variables are linked (Barbour, 1999). Thus, we assumed that the early qualitative pilot study would provide insights into designing the survey questionnaires and permitting a detailed understanding of the risk. Similarly, the survey outcomes would guide developing the core qualitative interview protocol. Besides, we anticipated that our strategy would produce either a complementary or contrasting picture to compare, triangulate, and validate or refute one outcome with another. Thereby, it was expected to illustrate the contexts through identified patterns of risk perception and risk mitigation, and discover any new theme from residents' experience to support or refute current evidence (Plano-Clark, 2010). Such analysis has been beneficial to provide a "whole greater than the sum of the parts" (Barbour, 1999, p.40) and thus, to draw a holistic interpretation from the final results to frame the complete story.

Qualitative Pilot Study. A qualitative mini pilot study was conducted as part of 'Qualitative Research Methods' course I attended in Winter 2017. With ethics approval for the course (ethics approval reference file number MGT5102), three interview participants were purposefully selected from the Ottawa-Gatineau community. These individuals had participated in the community health campaigns conducted previously for raising radon health awareness.

One of them had tested and mitigated the house for radon, and had advanced knowledge about the health risk from individual studies. The other two participants had some basic knowledge about radon but had not tested or mitigated their houses for radon. The interview protocol was developed step by step as part of the coursework based on the previously completed literature review, ideas from the protection motivation theory and feedback received each week from the professor. The first interview was transcribed and analyzed inductively following Charmaz's (2006) initial coding procedures. Several core constructs emerged from this analysis around risk awareness, different levels of perception, care for family members or children, positive adaptations and maladaptive behaviours. These were presented to the next class as an assignment and feedback was received from the professor on the quality of the data and coding procedure. Based on the feedback received, the interview protocol was revised to get more meaningful data and two subsequent interviews were conducted, transcribed and coded. One of the important findings of our pilot study, for example, was that presence of a child in the household influences radon-related awareness and adoption of preventive behaviour. This and similar findings helped in developing the survey instrument used in the quantitative part of the research.

Quantitative Part

The quantitative part was to test two groups of hypotheses by measuring the variables and statistically analyzing the numeric data. These were to provide measurable evidence in establishing associations (if not the probable cause and effect) and facilitating comparison of groups with the possibility to replicate the study. This is to be noted that the results of the study with a relatively small sample size could be generalized to the greater population only after proper weighting to control for the underrepresentation of certain demographics.

Qualitative Part

We considered the qualitative part to be relevant as this rigorous form of inquiry uses in-depth interviews and simultaneous observation of the contexts. Thereby, gathers data to understand the processes, generates detailed information about the context, and illustrates participants' voices through the in-vivo quotes to provide insight into the issue (Patton, 2015). From the population health perspective, the effectiveness of risk management strategies is contingent upon an in-depth understanding of the behavioural, environmental, social, and economic determinants that influence people's perceptions of the risk, raise concern, and drive decision-making (Beck et al., 2013). During my interactions with the residents, while conducting '*Radon Action Challenge'* campaigns, I noted a prevailing trend that people usually deny the very existence of the risk of radon and try to hold a notion of safety that is scientifically wrong and a cue to misunderstanding. Therefore, I decided to explore these aspects by employing various methods and theories that are suitable. Engaging in open conversation with the target population helps to understand the context and underlying determinants; and thereby, contributes to the designing of effective population health prevention strategies (Krieger, 2008; Public Health Agency of Canada, 2012).

Although using a focus group discussion (FGD**)** has some unique benefits, among them is understanding of group views. As out study focused on individual views, we did not used a FGD (Evidence Base, 2006).

Methods

In an exploratory sequential mixed design, we looked for the empirical evidence from both the a) qualitative interviews of purposefully selected residents with a mixed - open and semi-structured interview protocol including some close-ended queries and (b) quantitative survey with a structured questionnaire including some open-ended questions. Data was collected individually by me (student researcher) and with support from a research and information technology firm (Qualtrics) to design a web page and lodge the survey on the internet. Qualtrics provided some credits to the survey takers as they usually do, and this was included in their global invoice. No monetary remuneration was paid to the physical survey takers or interview participants for their time, but they were convinced to contribute to research for the greater benefit of the health of the population. However, a radon testing kit was made available to the interview participants as a token of appreciation to those who agreed to receive it and test their houses voluntarily.

Qualitative interview participants

The interviewees were selected purposefully from the neighbourhoods of Ottawa-Gatineau CMA. Efforts were made to reduce bias as much as possible by including participants from the diverse sociodemographic groups (Patton, 2015). Adopting a maximum variation sampling technique, we endeavoured to include members from all subgroups of people such as homeowner and tenant, male and female, young adult and elderly, different ethnic groups, levels of education, income and occupation categories. The final number of interviewees was 35.

Qualitative measures

Qualitative interviews were conducted using an interview protocol to explore themes and note sociodemographic situations of participants. The questions covered residents' source of radon health risk information, level of radon health risk awareness, the perception of susceptibility and severity of the risk, enablers and barriers in the context of residents' adoption of preventive actions or maladaptive risk behaviours. As mentioned, a mini-pilot study had been conducted earlier that helped to guide the development of a survey instrument to collect quantitative data and later to design the main qualitative interview protocol incorporating the outcomes of the quantitative analyses.

Quantitative survey participants

In a cross-sectional, non-experimental design, we conducted a complex survey to assess perception of radon health risk between two independent groups of residents from Ottawa–Gatineau census metropolitan area (CMA, Appendix 3). The Ottawa-Gatineau CMA is the only CMA that spans two provinces, its area comprised the capital city of Canada – Ottawa in Ontario side and Gatineau in Quebec side including neighbouring municipalities and suburban regions of both sides (Statistics Canada, 2016a). This 6,767 square kilometre area had an estimated resident population of 1,323,783 with 535,499 private dwellings in 2016 (Statistics Canada, 2016a). We applied a stratified two-stage cluster design based on postcodes. Group I and group II were property owners and tenants, respectively. We had a stratified random sample of 140 participants from each of the two cities and two neighbourhoods (Ottawa-Gatineau city centres and suburban areas of each). Homeowners (70%) were randomly selected via public access property rolls. Tenants (30% of the population who were not homeowners but renting houses) were chosen from the same city centres and neighbourhoods and selected randomly from the rental agency lists. Therefore, our final sample was assumed to be 560 (140x2x2). The neighbourhoods were chosen keeping in mind the possible variability in a) prevalence of the risk perception or radon awareness, b) urban versus suburban population, c) percentage of adult smokers (11.3% and 14.2%, respectively), d) lung cancer incidence (1 in 4,400 and 1 in 4.300), and e) average radon values (Health Canada, 2013; Lung Cancer Society, 2016; Statistics Canada, 2016a; Tobacco Use Statistics, 2018).

Selection Criteria

The selection criteria included living in a house that is in touch with the ground, spending at least four hours on the ground floor or in the basement of a home for at least one year. We excluded residents who live-in high-rise building, renters who moved in less than a year and anybody reside outside the defined CMA.

Relevance of Ottawa-Gatineau areas

The geometric radon level that is 79.1 Bq/M^3 in this CMA compared to 34.4 Bq/M^3 in Ontario and 41.7 Bq/M^3 in Canada (Gaskin et al., 2018b). Radon-related lung cancer risk is particularly relevant in Ottawa-Gatineau CMA as most of the houses are built over the Canadian Shield and there is a radiological anomaly emanating from the Gatineau Park that is also a part of the great Canadian Shield. Besides, these urban locations have homes that are among the oldest in the country with porous basements. Recent evidence of many radon-induced lung cancer cases, particularly among the non-smoking female population in the area (Canadian Cancer Society, 2016). As the community is bilingual, surveys were conducted both in English and French to meet participants' language preference.

Sample size calculation

We used the online sample size calculator of the University of British Columbia (2017;Appendix 4) to get the right inferences (α at .01 and desired power at .92) for proportions in comparing two independent samples of homeowner (P1) and tenants (P2). As the Households and the Environment Survey 2015 found that 55% of all households are aware of radon health risk in Canada. Here, the decimal fraction of population value is taken 0.55 (55%); thus, the fraction estimated for P1 (Homeowners) was .385 (70% of .55) and for P2 (Tenants) was .165 (30% of .55). Typically, about 30% of households in our target area are rented (Public Health Agency of Canada, 2012). Therefore, homeowners versus tenants' ratio is 7:3. The reason for using the awareness level was that we planned to measure and compare the same between two independent groups (homeowners and tenants) with regard to the national statistics. Thus, the online calculator gave us a sample size of 126 for each sample to be needed separately. However, considering the 90% response rate, the sample was raised to 140 (n=140) for each sub-group. As we have two level stratified sample (City-centres and suburbs of each city). Therefore, the total survey sample size was calculated to be 560 (N=560); where 280 (140x2) was for Ottawa and its suburbs; and 280 (140x2) was for Gatineau and its suburban areas. Figure 8 below displays a schematic of sample selection.

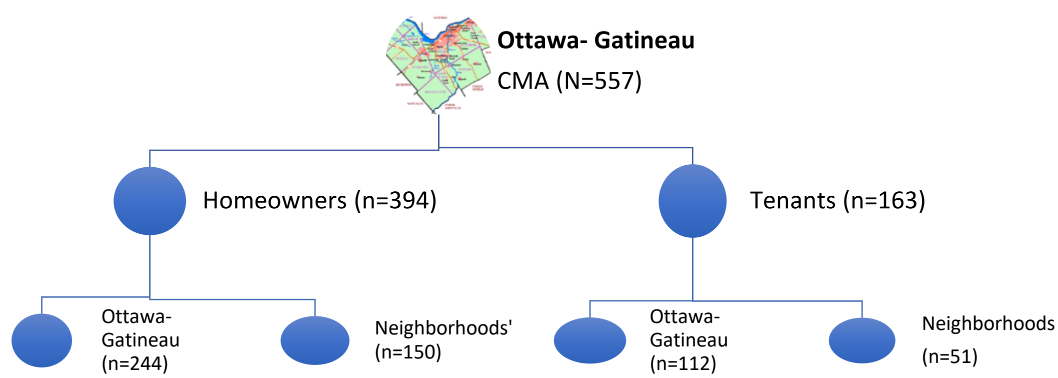

Figure 8. Schematic of Two Stage Sample Selection

Quantitative measures

The survey consisted of multiple-choice closed-ended as well as some open-ended questions. The dependent variables measured radon awareness, perceived susceptibility of the risk, perceived severity of the outcome, social influence, synergistic risk perception, concern about the presence of radon indoors, and behaviour like smoking in home. Although not identified as a significant factor in previous research (Huntington-Moskos, Rayens, Wiggins, & Hahn, 2016), our pilot study found that the presence of a child in the household influenced radon-related awareness and behaviour. Thus, this variable was included in this study. The dependent or outcome variables were residents' intention to test for radon and were measured in an ordinal scale, and residents' actual testing and mitigation done or not were expressed in binary responses such as 'yes' or 'no'.

The *anchored relative scales* rather than Likert scales were employed as research has identified the former to be more sensitive than the latter (Hampson, Andrews, Barckley, Lee, & Lichtenstein, 2003). The anchored relative scales had predetermined grading points unlike a range from 0 to 10 used by the Likert scale. This enabled having a clear idea about the distance between two measuring points. Paul Slovic scale was used to measure the worldviews of participants – specifically, whether residents possessed individualistic, hierarchic, communitarian/egalitarian or a shared worldview. This was informed by the work of Slovic-Peter (1998), Dake (1992) and Jenkins-Smith (1993) who measured worldviews through survey and found the results to be strongly linked to the public perceptions of risk (Please see the survey instrument in Appendix 24 and Appendix 25).

The control variables at the individual level included the sociodemographic factors like age, gender, education, occupation, income, race/ethnicity and homeownership or tenancy. The socioeconomic status (SES) was estimated based on participants' occupation and the total household in the previous year. The race and ethnicity were considered synonymous, and we used the categories exactly as used by the National Household and Environment Survey. These were European Canadian, Aboriginal Canadian, Visible Minority, but we kept options for those not willing to answer or ‘prefer not to respond’.

Data Collection Procedures

Quantitative data collection. Quantitative data were gathered through a mix of methods such as an online survey launched through a webpage and other social media (Twitter, Facebook), calling over phone and recording, and receiving the response by email. Traditionally, we would mail all (560) the bi-lingual surveys and expect at best 60% response rate. In that case, 336 survey responses would return. However, with clearance from the ethics office, we contracted a professional research firm (Qualtrics) to get a quick and better response rate. By running the survey online, we ultimately got over 90% response rate. In order to reduce response bias, we provide a short background, aims and objectives of our study. Assured respondents about the privacy and anonymity; cautiously kept the questions short and clear for easy understanding. Avoided difficult concepts or broke them down into simple language. We carefully structured the questions to maintain a logical sequence of events; avoided any leading questions but kept an exhaustive set of answer options.

The web-lodged survey contained a link to the consent form. The selection criteria were set in a way that could be filled only by people who fulfilled the inclusion criteria and then, could provide informed consent by going through the attached form and clicking a case that started the survey. However, as about 10% of residents have no access to the internet (Statistics Canada, 2018), we conducted a similar face-to-face survey at the community settings using pen and paper or an iPad where appropriate. This ensured the representation of that remaining 10 % of people.

Qualitative data collection. Following an interview protocol, face-to-face paper-based interviews were conducted with the voice recorded using a digital (Sony ICES/NMB-003) recorder and field notes were taken simultaneously. Data were transcribed verbatim and stored in a password protected external disk and kept in a safe to preserve for the next five years. On average, an interview lasted 60 minutes, and these continued until the thematic saturation was achieved (Hennink, Hutter, & Bailey, 2011). The interview data (verbal) were enhanced by adding observation (visual data), field notes (written), and photographs (visual) collected or taken from the spot to develop a contextualized understanding of the risk perception (Hennink et al., 2011).

Data Analysis

Quantitative data analysis. Descriptive and inferential analyses were conducted using SPSS 24 with 99% and 95% confidence intervals setting the alpha level at 0.01 and 0.05 (two-tailed) alternatively. Given there was no funding for the project, the freely available SPSS 24 in the Health Science library was used to analyze survey data. Initially, analyses for sensitivity for the methods were done. Descriptive statistics included frequency distributions and crosstabs to summarize and find correlations from the data. Univariate and bivariate analyses were conducted for the whole sample, subgroups (depending on homeownership and demographic variables), and outcomes (those with and without testing intentions, actual testing and mitigation). The Chi-square test of association used to determine whether study variables were associated with the intention to test for radon (Daniel, 1991). Multivariate ordinal logistic and binary regression conducted to identify predictors for the intention to test as well as actual protective behaviours that included whether or not the homes were tested and mitigated for radon. The details of each analysis are presented in the quantitative research chapter of this thesis. French data were translated into English, and all the analyzed results were reported in English with an abstract in French.

Qualitative data analysis. For the pilot project, we followed Charmaz's (2006) procedure of line by line coding using the gerund. For the main qualitative interviews, we followed Miles et al. (2014) and Braun and Clarke's (2006) recommendations for coding data. Thus, initial descriptive codes and then more focused codes were assigned to the transcribed interview texts. From the observation notes taken during the interviews, memos were inserted to the texts as relevant. A code list was prepared to show the codes and sub-codes with their descriptions and illustrations. A contact summary form (Miles et al., 2014) was added at the end of each interview outlining the important themes associated with the participant's perceptions and reported behaviours. Considering the larger volume of qualitative data, we used Atlas.ti for the focused coding and further analysis. We followed Braun and Clarke's (2006) thematic analysis procedures to find, refine, organize and categorize codes and ultimately, determined the patterns and final themes as described in the qualitative research chapter.

Mixed Methods Application and Data Interpretation

As per the mixed methods research approach (Creswell, & Plano-Clark, 2011), we corroborated the qualitative and quantitative findings to find links and relations between them. We identified points where one outcome complemented another and triangulated the results to come up with themes supported by both parts of the research. Besides the data generated through this project, some secondary data were collected that related to the existing building laws,

regulations, programs related to radon management policy in Canada and around the globe, the latest development in building codes, policy proposals designed by different organizations and initiatives taken by or under process with various agencies and levels of government bodies.

These were from credible sources like the latest published peer-reviewed literature, government agencies, private, intergovernmental or non-governmental organizations and from interactions with the key informants and researchers in this field. Consultation with the principal radon stakeholders, scientists, homebuilders, and health professionals on the research objectives helped to get a broader insight into the current state of affairs regarding radon research, policy and programs. The interpretation of conducted research findings and integration of ideas from experts in the field, and linking and comparing them to the latest development in the area helped to answer the mixed methods research questions in a comprehensive manner.

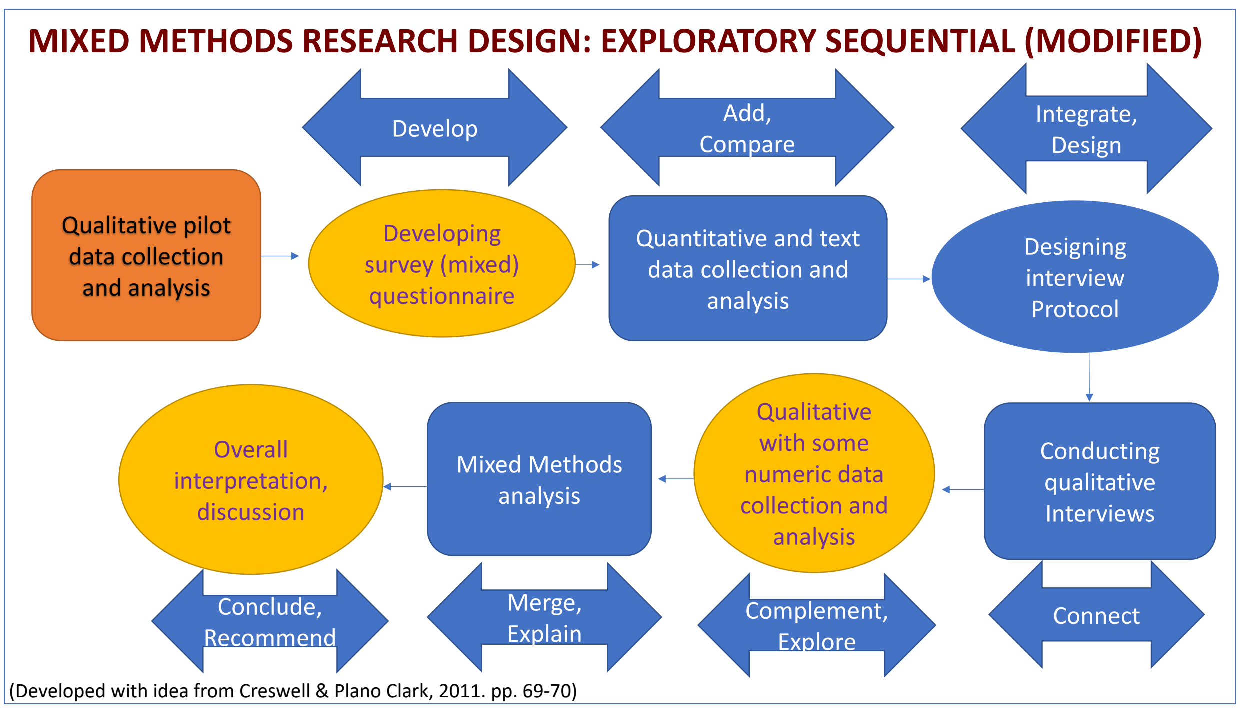

Figure 9. Sequence of the Mixed Methods Applied in this Project

(Reproduced with permission from Creswell & Plano-Clark, 2011)

Point of Interface

The point of interface or mixing of methods was made intentionally and systematically throughout the cycle of this project rather than keeping the quantitative and qualitative data separate to combine only at the end. The aim was to maximize the diversity and minimize the introduction of bias that can compromise the quality of each data type. Initially, mixing was done right from the conceptual and theoretical frameworks, and the process of mixing was continued through the designing of interview protocols and survey questionnaires. It remained in the data collection phase, as mentioned above, some numeric data were noted from the qualitative interviewees, and a few qualitative data were gathered from the survey through open-ended questions. Besides, during data analysis, some of the qualitative data, e. g., by counting the occurrence of themes (sources of information, average time passed or children sleeping in the basement, holding of worldviews) converted into quantitative scores to compare with quantitative frequencies. Although these were not from a representative sample, such analysis helped to explain, corroborate, compare and contrast one finding with another while conducting the mixed methods analysis as is customary in the field of mixed methods research (Sandelowski, Voils, & Knafl, 2009). For example, we considered how many cases a resident was motivated to test by the sense of care for children and how this corresponded to the quantitative findings. Finally, mixing was done during the final data interpretation when the quantitative results were compared and contrasted with the themes that emerge from the qualitative research (Morse & Niehaus, 2009). After the mixed methods analysis, a global discussion was conducted with the findings from both quantitative and qualitative studies. A schematic of these sequences of mixing of concepts, methods, analyses, interpretations and their outcomes related to each of these processes is presented in Figure 9 above.

Chapter Five: Quantitative Part

The quantitative part of the study was summarized in an article and submitted to the *Canadian Journal of Public Health*. This article was published online on December 19, 2018 at https://doi.org/10.17269/s41997-018-0151-5. The complete paginated journal issue came out on March 9, 2019 and available at: http://link.springer.com/article/10.17269/s41997-018-0151-5

Quantitative Research Article:

Radon, an Invisible Killer in Canadian Homes: Perceptions of Ottawa-Gatineau Residents

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Abstract

Objectives: Canadians have reason to care about indoor air quality as they spend over 90% of the time indoors. Although indoor radon causes more deaths than any other environmental hazard, only 55% of Canadians have heard of it, and of these, 6% have taken action. The gap between residents' risk awareness and adoption of actual protective behaviour presents a challenge to public health practitioners. Residents' perception of the risk should inform health communication that targets motivation for action. In Canada, research about the public perception of radon health risk is lacking. The aim of this study was to describe residents' perceptions of radon health risks and, applying a theoretical lens, evaluate how perceptions correlate with and predict protection behaviours.
Methods: We conducted a mixed online and face-to-face survey (n= 557) with both homeowners and tenants in Ottawa-Gatineau census metropolitan area. Descriptive, correlation, and regression analyses addressed the research questions.
Results: Compared to the gravity of the risk, public perception remained low. While 32% of residents expressed some concern about radon health risk, 12% of them tested and only 3% mitigated their homes for radon. Residents' perceptions of the probability and severity of the risk, social influence, care for children, and smoking in home correlated significantly with their intention to test; these factors also predicted their behaviours for testing and mitigation.
Conclusion: Health risk communication programs need to consider the affective aspects of risk perception in addition to rational cognition to improve protection behaviours. A qualitative study can explore the reasons behind the gap between testing and mitigation.
Keywords: Air pollution. Indoor. Radon. Risk. Perception. Canada.

Résumé

Objectifs : Les Canadiens ont de bonnes raisons de se préoccuper de la qualité de l'air intérieur, car ils passent plus de 90% de leur temps à l'intérieur. Bien que le radon domiciliaire (RD) cause plus de décès que tout autres risques environnementaux, seulement 55 % des Canadiens en ont déjà entendu parler, et d'entre eux seulement 6 % ont pris des mesures concrètes pour l'éradiquer. L'écart entre la sensibilisation aux risques et la prise de mesures de protection réelles par les résidents constitue un défi pour les professionnels de la santé publique. La perception des résidents face aux risques associés au RD devrait guider la communication en matière de santé pour cibler la motivation. Au Canada, très peu d'études portant sur les perceptions de la population face aux risques associés au RD ont été réalisées. Le but de cette étude est de décrire les perceptions qu'entretiennent les occupants de bâtiments résidentiels face aux risques pour la santé associée au RD et évaluer comment ces perceptions sont corrélées aux comportements de protection, notamment en appliquant la théorie de la motivation et de la protection.
Méthodes : Nous avons réalisé une enquête mixte en ligne et en personne (n = 557) auprès de propriétaires et de locataires de la région d'Ottawa-Gatineau. Des analyses descriptives, corrélationnelles et des analyses de régressions ont été effectuées en fonction de nos questions de recherche.
Résultats : En comparaison à la gravité des risques, les perceptions du public demeurent faibles. Bien que 32 % des résidents avoir exprimé des préoccupations au sujet du danger que représente le radon pour la santé, seulement 12 % d'entre eux ont réalisé des tests à domicile et seulement 3% ont pris des actions concrètes pour réduire les risques. Les perceptions des résidents quant à la probabilité et à la gravité des risques du RD sur leur santé, l'influence sociale, les soins prodigués aux enfants, ainsi que le tabagisme à la maison étaient significativement corrélés avec leur intention de réaliser un test. Ces facteurs ont également prédit leurs comportements en lien avec l'utilisation du test et les actions entreprises pour diminuer les risques.
Conclusion : Les programmes de communication sur les risques du RD sur la santé doivent tenir compte des aspects affectifs associés à la perception des risques, en plus de tenir compte du niveau de connaissances pour améliorer les comportements de protection. Une recherche de nature qualitative serait nécessaire pour explorer les raisons qui expliquent l'écart entre le taux d'utilisation des tests de détection et les actions concrètes pour diminuer les risques.
Mots-clés : Pollution de l'air. Radon domiciliaire. Perceptions du risque. Canada.

Radon, an Invisible Killer in Canadian Homes: Perceptions of Ottawa-Gatineau Residents

Introduction

Canadians have reason to care about indoor air quality as they spend over 90% of the time indoors (Leech et al., 2002; Setton et al., 2013). Having the world's most abundant reserves of high-grade uranium (U^{238}), Canadian land emits higher levels of soil gas radon (Rn^{222}) than any other country (Natural Resources of Canada, 2014). In urban areas, people of lower income levels are most likely to rent poorly ventilated basements or houses that are in contact with the ground (Briggs et al., 2008). Airtight energy–efficient homes have pressure gradients between the heated indoors and chilly outdoors, which create conditions for harmful gases in the soil to enter the house (Fro ka, & Jilek, 2014; Henderson et al., 2012). Inside such dwellings, the radioactive gas builds up during the long winter months when doors and windows remain closed. Radon further degrades by emitting alpha particles which upon inhalation prompt mutations of lungs' DNA leading to cancer (Gustavino et al., 2014). In Canada, about 7% of homes have radon gas above the federal reference level of 200 Bq/m^3 (Health Canada, 2013). Contingent on the long winter, construction design, older houses, urban location, and radiological anomaly in Gatineau Park, Chelsea, Kanata, Stills-ville Ottawa- Gatineau residents face an elevated risk of exposure to radon.

There is no threshold for the carcinogenic effect of radon, and most lung cancers occur from exposure to concentrations below this set level (Peterson et al., 2013), and such exposures are reported to increase the incidence of lung cancer (Henderson et al., 2012). Annually, at least 3,200 Canadians die from radon-induced lung cancer, accounting for 16% of all (smokers, ex-smokers, and non-smokers) lung cancer deaths and making radon the leading cause of lung cancer deaths among non-smokers and the second highest among smokers (Statistics Canada, 2016). Compared to the general population, children (increased breathing rate), women (passing prolonged time indoor), and men smokers (synergistic effect of radon) with lower socio-economic status are disproportionately affected by exposure to radon (Hill et al., 2006). Lung cancer risk from radon exposure is up to ten times higher among smokers compared to non-smokers due to a synergistic effect (U.S. Environmental Protection Agency, 2012). Children in households with less-educated parents are more likely to be exposed to second-hand smoking (Klepeis et al., 2013). Due to the public perception of low risk, radon has the highest impact on the health of the population among all environmental pollutants (Signorelli & Limina, 2002).

Despite multiple efforts, the National Radon Program (NRP) lags behind with regard to the desired public uptake (Statistics Canada, 2016). In 2015, at least 55% of all Canadian households indicated hearing about radon, but only 6% of them tested their homes for it (Statistics Canada, 2016). The gap between risk awareness and actual testing rates presents a challenge to public health practitioners. So far, practitioners assumed that better communicated information, enforced guidelines, and tax rebates would be among the best solutions for radon health risk (hereafter 'the risk') management (Spiegel & Krewski, 2002). However, studies in the United States (Hahn, 2014), the United Kingdom (Poortinga et al., 2011), and Ireland (Dowdall et al., 2016) showed that taking regulatory actions, offering rebates, and even providing free test kits and services could not significantly improve the program uptake. Thus, the key question—how to motivate the target population individually and collectively—remains unanswered (Hevey, 2017).

Even after informing (cognitive awareness) residents that their houses might have a high level of radon and it might pose a serious health threat, protective actions remained low (Field et al., 1993). Social science research has argued that the success of a population-level health promotion program is contingent upon the motivation of key decision makers at the household level (Lorang, 2001). We believe that residents' perception of the risk should inform health communication programs targeting motivation. In Canada, research about the public perception of radon health risk is lacking. Therefore, in this study, we employed theory-based tools to understand the determinants related to residents' perceptions of the risk.

We sought to determine whether they were motivated to change their behaviour due to cognitive awareness alone, or whether there was an effect of emotional influence related to the limbic part of the brain controlling affective behaviours (Lorang, 2001). Such understanding can guide strategies to enhance uptake of the program. This article reports the quantitative findings of a mixed methods study conducted in winter 2018.

Theoretical framework

Exposure to a health risk communication creates a dual appraisal process: (a) threat appraisal and (b) coping appraisal (Witte, 1992). Threat appraisal is the assessment of the chance (susceptibility) of contracting a disease and evaluating its seriousness (severity). A coping appraisal comprises response efficacy and self-efficacy. Response efficacy is the expectation that carrying out recommendations would eliminate the threat. Self-efficacy denotes the belief in an individual's ability to accomplish suggested actions without failure (Witte, 1992).

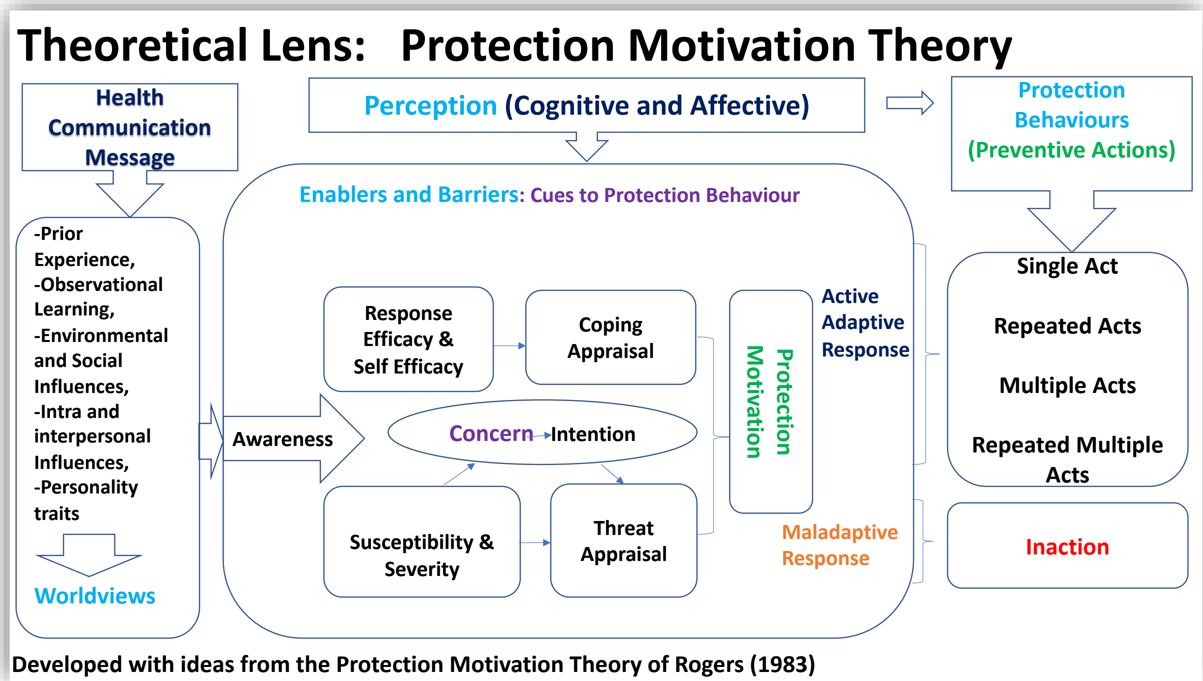

Figure 10. Theoretical Lens: Protection Motivation Theory

(Second appearance of Figure 7 as it was published with this article)

Thus, the stronger a threat appraisal, the more an individual engages with the coping behaviour. The Protection Motivation Theory (PMT) specifies how these perception processes lead an individual to adopt either an active adaptive or maladaptive coping mechanism in response to a health risk (Rogers, 1983). These, in turn, are fortified by observational learning (someone died from radon induced lung cancer), internal persuasions (lifestyle, smoking), intrapersonal traits (caring for family), and external environment (social influence) leading to fear arousal and developing the intention to take action. These perception processes combined with multiple influences generate a broader perception (worldview) about the risk that shapes the protection motivation (intention to test) and ultimately leads an individual to the actual adoption of coping behaviours (Boer & Seydel, 1996). Alternatively, the maladaptive responses place people at additional risk as they miss the opportunity to take preventive actions.

Therefore, the PMT has four dynamics: (a) perceived probability (exposure to radon), (b) perceived severity of a threatening event (having lung cancer), (c) response efficacy of the recommended intervention (testing and mitigation can eliminate the threat), and (d) self-efficacy (confidently taking action). Thus, protection motivation is the result of informed threat and coping appraisal, which facilitates the adoption of protective health behaviours (Boer & Seydel, 1996) (Figure 10 above).

Appraising homeowners' perceptions within the above fundamental logics of PMT might help to enhance understanding of the motivation dynamics and identify strategies to influence protection behaviours. Therefore, this study examined the PMT components in a Canadian context to provide insight into homeowners' perceptions of radon health risk. The PMT has been previously applied in health research to influence and predict various health-related behaviours related to reducing alcohol consumption, enhancing healthy lifestyles, improving diagnostic health behaviours, and preventing diseases (Boer & Seydel, 1996). A thorough understanding of homeowners' perception of the risk through this theoretical lens can advance the PMT research agenda to promote awareness of health risks and encourage innovative approaches by policymakers and professionals to address the issue.

Research Questions and Hypothesis

The primary research question was as follows: How do Ottawa-Gatineau residents perceive and act in response to the health risk of radon? In addition to inquiring about the risk perception phenomena and related worldviews, we sought to answer the following sub questions:

i) What are the associations of residents' intention to test for radon, with the following variables: Perceived radon health risk susceptibility, severity, synergistic risk of radon with smoking, smoking in home, care for children, and social influence? ii) How do these variables (mentioned in i) predict residents' efficacy in adopting protection behaviours (testing and mitigation of homes for radon)?

We hypothesized that there would be significant associations between perceived radon health risk susceptibility, severity, synergistic risk perception, smoking in home, care for children, and social influence, with residents' intention to test for radon. Likewise, these variables would predict residents' adoption of protective behaviours.

Methods

Sampling and data collection protocol. We surveyed homeowners and tenants (included for the first time in such a study as a comparison group) of Ottawa and Gatineau census metropolitan area (CMA) who met the following criteria: resident in a house with a basement or a house in contact with the ground for over one year. Participants were randomly selected from the residents' panel with Qualtrics, a platform frequently used in standard research studies (Farris et al., 2018; Glodstein et al., 2018). Participants received email invitations, along with a link to the online survey in both French and English. We conducted an equivalent, face-to-face version of the survey using iPads. Some participants filled out the survey and returned it by email, and others completed the face-to-face version in the community settings to cover up respondents who could not take the interview online. The University of Ottawa's Institutional Review Board approved the study and data collection protocols (file number: H10-17-03;Appendix 1).

Participation was voluntary and anonymous. All participants went through the informed consent form and checked option in affirmative to be able to go ahead with the survey. We estimated the sample size to be 560.

Instrument and Measures

Survey Questionnaire. The 41-item survey instrument was developed from ideas from the National Radon Survey 2011. However, there have been some modifications done based our initial pilot qualitative study and literature review. It included a mix of closed- and open-ended questions. We measured the independent variables such as residents' perception of radon health risk susceptibility (Q13. How likely radon may cause any harm to your or any of your family member's health? And perception of severity (Q14. Does radon cause any severe or adverse health effect?) of the risk across homeowners and tenants. We also measured internal factors such as smoking in home (Q30. Does anybody smoke cigarette in your home?) and synergistic risk perception (Q33. How do you rate the risk of smoking and radon combined compared to the risk of smoking alone?). The intrapersonal factor included care for children (Q5. Does a child or anybody live or spend more than four hours per day in the basement or ground floor?) and external persuasion like social influence (Q28. How many people you know who have tested their homes for radon?). Although the last three variables were measured in previous research in different settings (Butler et al., 2017; Huntington-Moskos et al., 2016), our pilot qualitative study conducted in winter 2017 helped to shape the questionnaire in a Canadian context.

We employed an anchored relative scale rather than Likert scales as previous research identified the former as being more sensitive than the latter (Hampson et al., 2003). The anchored relative scale quantified grading points with specific narratives rather than the inexplicit ranges. The open-ended questions explored residents' depth of knowledge and points of views regarding various aspects of radon health risk. The outcome (dependent) variables included intention to test (have you the intention to test your home for radon?), tested home for radon (have you ever tested your home for radon?), and mitigated home for radon (did you fix or mitigate your home after testing?). The efficacy was enquired by asking about repeated actions (did you test after mitigation?).

The open-ended questions explored residents' general awareness (what do you know about radon?) and points of view (worldviews) regarding risk management (is it an individual or overall societal problem? Then, who should be responsible for fixing it?). We collected socio-demographic (control) variables such as age, gender, race/ethnicity, education level, total household income, and home ownership or tenancy to compare how the risk perceptions vary with these features. We followed the criteria used in the National Households and the Environment Survey (2015) to classify gender, age group, race/ethnicity, education, and income groups. Participants voluntarily identified themselves and chose their groups.

The instrument was revised by two personnel working with the NRP at managerial position. We also conducted a reliability analysis of our perception scales (susceptibility and severity of the risk) and obtained an internal consistency score of 0.74 (Cronbach's alpha) with a 2-item adapted scale.

Analysis

Respondents completing < 80% of the survey questions accounted for less than 10% of the total sample and were excluded from further analysis. This was possible as we got a higher response rate. Because our focus was on Ottawa-Gatineau residents, we eliminated all participants who completed the survey from outside this area. With an over 90% response rate, our final sample (n = 557) consisted of 394 (71%) homeowners and 163 (29%) tenants. The response rate was high for taking the survey using all the most convenient media such as online - using popular social media (Twitter, Facebook) as well as face-to-face using iPad at the community settings. We conducted descriptive and inferential analyses using IBM SPSS 24, setting the confidence intervals at 95% and 99%; alpha at 0.05 and 0.01 (two-tailed) alternatively.

Descriptive statistics included frequency distributions to summarize the data. We conducted univariate analyses for the entire sample, subgroup (homeownership and demographic characteristics), and outcome variables. We conducted planned as well as posthoc (not included in the prior statistical analysis plan) sensitivity analyses to test the robustness and consistency of the outcomes applying different approaches, assumptions (normality), methods, sub-groups, factorial designs and outcome definitions (Thabane et al., 2013). These included identifying any outliers and conducting analyses with or without them; dealt with missing data using multiple imputation techniques (used multiple imputed datasets that generated unbiased estimates accounting for the within- and between-dataset variability) as it is the best available method of dealing with missing data under the assumption that data are missing at random (McKnight, McKnight, Sidani, & Figueredo, 2007). However, the results remain unchanged i.e. robust based on the magnitude, direction or statistical significance of the estimates.

We used Pearson's chi-square test of associations and likelihood ratios to determine whether the risk-related perception variables were associated with residents' intention and actual performance of protection behaviours (testing and mitigating). We arranged the data to meet all relevant assumptions related to multicollinearity, outliers, normality, homoscedasticity and independence of residuals (Tabachnick & Fidell, 2013).

We conducted ordinal regressions to identify predictors of intention to test as susceptibility of the risk was measured in a five-point ordinal scale. Binary logistic regressions were used to determine actual testing and mitigating behaviours as both the outcome variables were dichotomized into 'yes' and 'no'. We examined the fit of our proposed model, controlled for age, gender, race/ethnicity, education, total household income, and home ownership. In the regression analysis, initially the variables were entered simultaneously; and then, a forward conditional method was used in each of the models.

Results

Sample characteristics. Our sample proportionately represented socio-demographic features of Ottawa-Gatineau CMA residents. Table 2 below presents these characteristics and their associations with residents' intention to test their homes for radon. We found significant associations ($p < 0.001$) of residents' homeownership, gender, and age groups with their intention to test for radon but not with their race/ethnicity, education and income levels. The results of the sensitivity analyses and primary findings were similar; thus, the outcomes remained robust.

Table 2. Sociodemographic Characteristics versus Intention to Test Homes for Radon

Residents' Intention to Test Homes for Radon							
Characteristics	Total Sample (N=557)		Yes		No		Associations (Significance)
	Number	%	Number	%	Number	%	χ2 (p)‡
Homeownership							
Owners	394	71	179	80	215	65	14.2* (.00§)
Tenants	163	29	46	20	117	35	
Gender							29.42*(.00§)
Male	291	52	88	39	203	61	
Female	224	40	121	54	103	31	
Age groups							
18-24 year	83	15	46	20	37	11	
25-34 year	58	10	35	16	23	7	
35-44 year	59	11	33	15	26	8	85.8* (.00§)
45-54 year	85	15	50	22	35	11	
55-64 year	106	19	9	4	97	29	
65 and above	166	30	52	23	114	34	
Race/Ethnicity							
EC	375	67	146	65	229	69	
AC	14	2.5	5	2	9	3	1.9* (.58)
Visible Minorities	120	21	55	24	65	20	
Education							
High School	70	13	25	11	45	14	
College	135	24	54	24	81	24	9.0† (.53)
University	346	62	146	65	200	60	
Income groups							
>$40K	60	11	28	12	32	10	
$41k-50k	147	26	60	27	87	26	
$51k-75k	94	17	36	16	58	17	2.1* (.83)
$76k-100k	106	19	44	20	62	19	
$101-150k	68	12	28	12	40	12	

EC- European Canadian, AC- Canadian Aboriginal, *Pearson Chi-Square (χ2); †Likelihood ratio; ‡Asymptotic significance (2 sided); §Significant association

However, homeowners, females, and older adults had greater intention to test than tenants, males, and young adults. Although European Canadians, university-educated, and lower-middle-income residents showed a higher level of intention to test their houses for radon, these associations were not statistically significant.

Table 3. Sociodemographic Characteristics versus Preventive Behaviours

	Residents Ever Tested Homes for Radon							Mitigated homes for radon						
Characteristics	Total Sample (N=557)		Yes		No		Associations (Significance)	Total Sample (N=557)		Yes		No		Associations (Significance)
	N	%	N	%	N	%	χ2 (p‡)	N	%	N	%	N	%	χ2 (p‡)
Homeownership **Owners** **Tenants**	394 163	71 29	63 4	94 6	331 159	68 32	19.9* (.00§)	394 163	71 29	17 0	100 0	377 163	70 30	7.7* (.00§)
Gender **Male** **Female**	291 224	52 40	34 31	51 46	257 193	52 40	2.8* (.24)	291 224	52 40	10 8	56 44	281 216	52 40	1.5* (.46)
Age groups **18-24 year** **25-34 year** **35-44 year** **45-54 year** **55-64 year** **65 and above**	83 58 59 85 106 166	15 10 11 15 19 30	19 11 10 9 5 13	28 16 15 13 8 19	64 47 49 76 101 153	13 10 10 15 21 31	21.5† (.00§)	83 58 59 85 106 166	15 10 11 15 19 30	6 3 5 2 0 2	35 18 29 12 0 6	77 55 54 83 106 164	14 10 10 15 20 31	16.0† (.00§)
Race/Ethnicity **European Canadian** **Canadian Aboriginal** **Visible Minorities**	375 14 120	67 3 21	36 2 20	54 3 30	339 12 100	69 3 20	6.6* (.08)	375 14 120	67 3 21	10 0 6	56 0 33	365 14 114	68 3 21	2.2† (.53)
Education **High School** **College** **University**	70 135 346	13 24 62	7 17 42	10 25 63	63 118 304	13 24 62	12.0* (.28)	70 135 346	13 24 62	1 4 13	6 22 72	69 131 333	13 24 62	11.9 (.29)
Income groups **>$40K** **$41k-50k** **$51k-75k** **$76k-100k** **$101-150k**	60 147 94 106 68	11 26 17 19 12	11 19 10 9 12	16 28 15 13 18	49 128 84 97 56	10 26 17 20 12	5.73* (.33)	60 147 94 106 68	11 26 17 19 12	3 4 1 3 5	18 23 6 18 29	57 143 93 103 63	11 26 17 19 12	5.89 † (.31)

*Pearson Chi-Square (χ2); †Likelihood ratio; ‡Asymptotic significance (2 sided); §Significant association

However, when it comes to taking actual protective actions, homeownership and age groups were only significantly correlated to testing and mitigation homes for radon (Table 3 above). Further analyses showed that males and young adults exceeded their counterparts in testing, though the university-educated and the upper-middle-income group of people took the lead in mitigating their homes for radon.

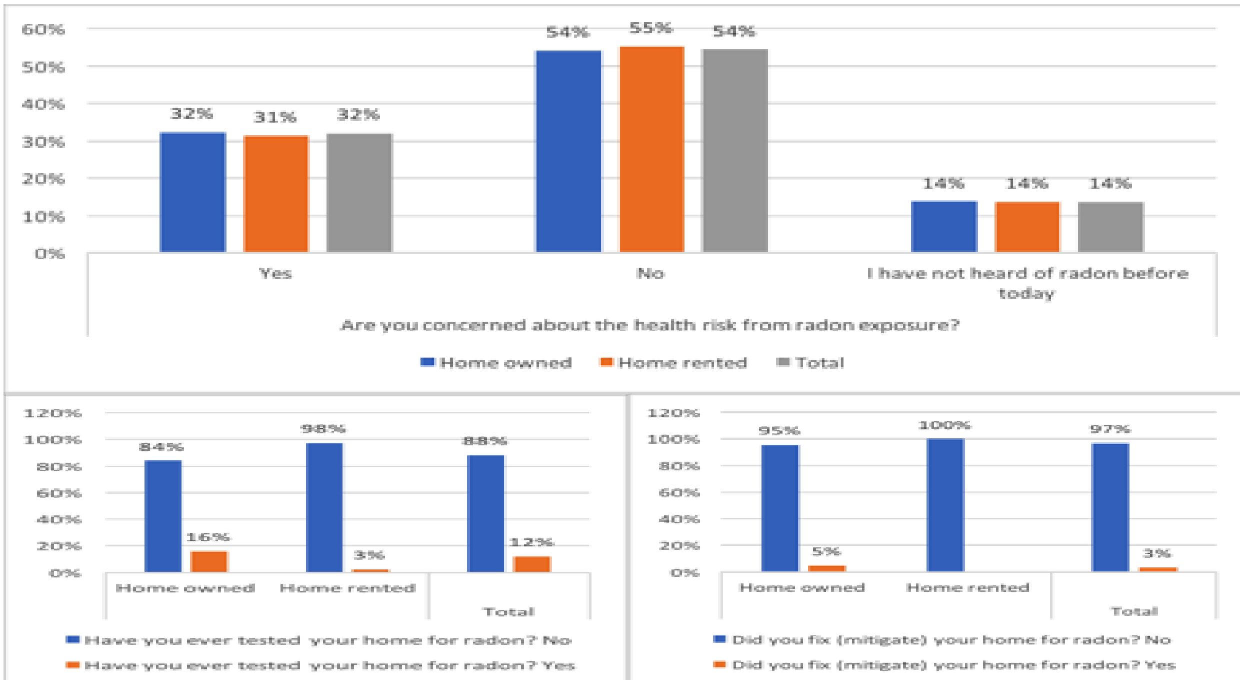

Figure 11. Residents' Concern about Radon Health Risk; Actual Testing-Mitigation Behaviours

Regarding indoor air quality, more people expressed concern about dust/dust mites (29%) and mould (27%) than radon (20%). Among the residents concerned about radon, 39% described it as a radioactive gas. Their three primary sources of information were media (54%), Health Canada (19%), and Internet browsing (17%).

Figure 11 above shows that overall only 32% of residents had concern about exposure to radon health risk, only 12% of them tested homes for radon, and just 3% of them mitigated their homes to reduce the risk. Among those who mitigated, 94% retested after mitigation ($p < 0.001$), showing the efficacy of adopting protection behaviours. Although 3% of tenants also tested, none of them mitigated their houses for radon.

Our analysis showed that 93% of homeowners and 85% of tenants spent more than four hours either in the basement or on the ground floor. This variable had a significant correlation with testing for homeowners ($p = 0.01$) but not for tenants ($p = 0.904$). Both smoking in home and synergistic risk perception were significantly associated with the intention to test by homeowners ($\chi2 = 107.12, 172.42$; $p < 0.001, < 0.001$) and tenants ($\chi2 = 42.17, 88.22$; $p < 0.001, < 0.001$). Our data showed that 21.8% of homeowners and 5% of tenants had at least one child living in the basement or on the ground floor, a situation that had strong associations with the intention to test for both homeowners ($\chi2 = 81.82$, $p < 0.001$) and tenants ($\chi2 = 13.08$, $p < 0.001$).

Similar strong associations were found between social influence and intention to test for both homeowners ($\chi2 =41.66$; $p < 0.001$) and tenants ($\chi2=4.54$, $p = 0.03$). When asked about their worldview about radon, 28% of respondents said that they are concerned about their health since radon exposure affects everybody (egalitarian). Over 26% said that radon affects individual persons, so they (homeowners) are responsible for fixing it (individualist). About 25% said that although property owners and tenants have responsibilities, they should get a tax rebate according to their income level for mitigating their homes (Shared views). Nearly 21% said that as this is a population health problem, the government or responsible agency is responsible for fixing it (Hierarchic). These opinions did vary significantly by residents' gender ($\chi2 = 35.20$, $p<0.001$), age ($\chi2=29.24$, $p < 0.01$), education ($\chi2=32.36$, $p < 0.001$), and income levels ($\chi2 = 27.49$, $p<0.02$) but not with homeownership and race/ethnicity.

Results to answer the research questions

We assumed that there would be significant associations between perceived radon health risk susceptibility, severity, synergistic risk perception, smoking in home, care for children, and social influence, with residents' intention to test for radon.

Table 4. Outcomes of Ordinal and Binary Regression Modeling

Variables	Intention to test				Tested home for radon				Mitigated home for radon			
	Estimate/ β	SE	Wald/ Std. β	P	Estimate/ β	SE	Wald/ Std. β	P	Estimate/ β	SE	Wald/ Std. β	P
Perceived susceptibility of radon risk*	2.0	.65	10.3	.00§	18.8	.36	2762.3	.00§	18.5	.66	787.5	.00§
Perceived severity of radon risk†	2.5	.42	36.8	.00§	2.4	.62	15.5	.00§	20.3	.66	936.9	.00§
Synergistic risk perception‡	-3.6	.37	97.7	.00§	-3.4	.41	67.9	.00§	-2.5	.64	15.7	.00§
Smoke in home‡	-2.0	.35	35.7	.00§	-3.5	.39	81.7	.00§	-4.0	1.03	15.1	.00§
Care for children‡	-2.0	.49	17.7	.00§	-5.4	.55	98.9	.00§	-4.6	1.04	19.9	.00§
Social influence	2.3	.60	14.7	.00§	-6.5	.60	118.8	.00§	-4.9	1.04	22.8	.00§

*Ordinal regression model fit statistics for intention to test are Likelihood = 21.47, $p < 0.001$, and X2 = 100.43, df=4.
†Ordinal regression model fit statistics for intention to test are Likelihood = 20.09, $p < 0.001$, and X2 = 75.04, df=3.
‡Binary regression model, Hosmer and Lemeshow test's X2 =47.42, $p<0.001$, df=4.
§Values refer to the predictors that are significant in the model. SE=standard error of β; Std. β=standardized beta, $\chi 2$= Chi-Square statistic, df=degree of freedom.

Likewise, we further assumed that these variables would predict residents' adoption of protection behaviours that are to take actual actions such as testing and mitigation of homes for radon. Table 4 above presents the outcomes of ordinal and binary logistic regressions that show the perception variables were significantly associated with residents' intention to test for radon as well as predicted residents' efficacy in actually adopting the protection behaviours.

Discussion

Our purpose in this study was to describe residents' perceptions of radon health risks and to evaluate how perceptions correlate with protection behaviours, applying the protection motivation theoretical lens. We examined the perception of radon health risk of an illustrative sample of Ottawa-Gatineau residents. In doing so, we compared the obtained measures on the perception variables of interest with residents' socio-demographic features and identified mixed associations with their intention to test and actual protection behaviours. Our analyses showed significant associations of perception variables with residents' intention to test for radon. The same variables meaningfully predicted residents' actual protection behaviours and, thus, confirmed the hypotheses. The results of our sensitivity analyses were similar to the primary analysis that indicates consistency or robustness of the outcomes. These findings correspond with the results of studies conducted by Hahn et al. (2014) in the US and Butler et al. (2017) in the UK.

A few quantitative studies in Canada have assessed public perception of environmental health risks in general. Krewski et al. (2006) conducted a national survey on health risk perception and looked into 30 common health hazards. A more focused study by Spiegel and Krewski (2002) evaluated health risk perception of radon along with three other health hazards affecting residents of high-radon areas in Canada. They examined residents' compliance with the radon guideline and concluded that the Canadian Radon Guideline is not effectively prompting homeowners to reduce radon exposure (Spiegel & Krewski, 2002). Our findings support this conclusion that compared to the gravity of the risk, residents' perception level remains low.

Although those studies credibly supported the federal government's initiative to develop a guideline, no follow-up study purposefully focused on radon health risk perception to support the National Radon Program of Health Canada. This study successfully fills that scholarly gap in the literature.

As stated before, we included tenants for the first time in a study and this led to some notable findings. Although few in number, compared to 16% homeowners, 3% tenants also tested their houses for radon (Figure 11) due to having concern for their children living in the basement. However, none of them mitigated their homes. An apparent reason for this is the lack of authority to do so; nonetheless, there exists no law that gives tenants the right to hold property owners responsible for such mitigation. Homeowners who mitigated their homes similarly tended to have children sleeping in the basement; additionally, they had observed others taking such mitigation action or had heard of people who had radon-induced lung cancer.

Application of these perception points may, however, create fears and apprehensions among tenants and occupants of public buildings who, for the time being, are not required to measure and mitigate radon. These can also dissipate the ambiguity in the program on radon health communication and help to deliver the health communication messages to the right audience in the right manner and, thus, can open up a new avenues for the public health preventive interventions. Again, the significant correlation between having children living in the basement or on the ground floor and taking actual protective behaviours might have biological plausibility. Here, the targeted health communication message that can stir the affection part relating to the inner cortex or limbic brain related to emotion would yield a better outcome compared to those emphasizing only the rational cognitive part pertaining to the neocortex.

These findings warrant further exploration of social influence through an in-depth qualitative study to test whether motivation works under the affective familial or social influence that can open the way to make protective behaviours a norm in our society.

Although our study targeted one metropolitan area, the Ottawa-Gatineau CMA spans two provinces in the capital region and covers both English- and French-speaking populations and, thus, filled a critical gap in measuring residents' perception of radon health risk across two official linguistic groups in Canada. Thereby, a systematic understanding of homeowners' perceptions through the protection motivation theoretical lens advances the PMT research agenda and puts forward evidence for innovative approaches to be considered by policymakers and professionals in addressing the critical public health issue of radon.

Limitations

Our study is limited in demographic scope. We may have overlooked demographic diversities and cultural subtleties in selecting the sample online. Our sample did include tenants, but the lack of variability in the scores may have affected the relationship between them. Furthermore, residents who took the survey did so voluntarily and included those who have access to the Internet; therefore, we collected proportional responses offline using iPad to include the remaining 10% of residents with no access to the Internet (Statistics Canada, 2018). Our study included only residents in Ottawa-Gatineau and should be understood in the context of this population. Though the sample was in proportion to the demographic features of the Canadian population, we cannot claim it to be representative of the whole Canadian demography. A future study with a national representative sample would provide stronger evidence-base to support the design of national health communication programs focusing on residential radon risk mitigation.

Conclusion

In this study, we tested the hypothesis that those with higher levels of perceived susceptibility, severity, synergistic risk perception, smoking in home, care for children, and social influence would be more likely to have the intention to test as well as to demonstrate protection behaviours regarding testing and mitigating their homes. Statistical analyses of our survey data confirmed this hypothesis in a Canadian context. Variables reflecting public perception of radon health risk did not always convert into the protection behaviours that could be explained by biological plausibility. Nonetheless, through the protection motivation theoretical lens, we have now understood that residents' perceptions of health risks of radon are the markers of intention to test their house for radon as well as the clear predictors of actual risk mitigation behaviours.

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Author's Note:

This article reports the quantitative part of a mixed methods research project conducted for a doctoral dissertation during winter 2018 at the University of Ottawa.

Compliance with ethical standards: The University of Ottawa's Institutional Review Board approved the study and data collection protocols (file number: H10-17-03;Appendix 1).

Conflict of interest: The authors declare no conflict of interest.

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Chapter Six: Qualitative Part

As mentioned before, a pilot study was conducted in winter of 2017. Based on that and with insight from the survey results, a semi-structured interview protocol was designed under the close supervision of Professor Dr. Samia Chreim (my co-supervisor). We conducted 35 interviews in total. The qualitative part of our study was summarized in an article and submitted to the *BMC Public Health*. The article pasted below is currently accepted for publication and in press waiting for publication. Assigned DOI: 10.1186/s12889-019-7449-y

Qualitative Research Article:

Residents' Perceptions of Radon Health Risks: A Qualitative Study

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Abstract

Background: Radon is a high impact environmental pollutant and is the second leading cause of lung cancer in Canada. Building design, extended winter, and geographical location expose residents of Ottawa-Gatineau (the national capital region in Canada) to an increased risk. It is surprising that residents have an inadequate awareness of the risk - despite its gravity - and have taken minimum preventive actions. This study explores perceptions of radon health risk and examines the factors that enable and hinder the adoption of preventive measures among Ottawa-Gatineau residents.
Methods: We conducted semi-structured interviews with 35 residents with varying demographic characteristics to inquire about their knowledge and perception of radon, and to explore their views of enablers and obstacles in taking action to reduce radon risks. Thematic, inductive data analysis was undertaken.
Results: The results indicate that: 1) Residents obtained information on radon from various sources that include the media, their education or occupation, their social networks, and home renovation events. Limited references were made to the National Radon Program responsible for testing for radon and informing residents. 2) Awareness of radon risk varied, and the knowledge retained by some residents is insufficient to adequately protect their health. 3) Enablers for taking protective action included: having an understanding of the risk along with health consciousness; caring for family and children; knowing others who had contracted lung cancer and having financial resources. Obstacles consisted: lack of awareness; cost; lack of home ownership; and potential difficulty in selling the house. 4) Residents attributed primary responsibility to public agencies for disseminating information, and incentivizing or mandating action through more stringent regulation.
Conclusion: Risk perceptions are subjective, and are influenced by micro and macro level factors. Inducing protective action to reduce risk will require comprehensive interventions taking into account dual perceptions of the threat. Future research can explore the dual aspects of risk perception and examine the contents of the risk communication message. Policy should address the shared responsibility of both governments and residents in tackling the issue.
Keywords: Radon; Risk perception; Testing; Mitigation; Enabler; Barrier; Health Communication, Policy.

Residents' Perceptions of Radon Health Risks: A Qualitative Study

Background

Radon is a ubiquitous environmental pollutant that poses a significant health risk, especially in cold countries (World Health Organization; WHO, 2009). In Canada, radon kills at least 3,200 people annually, making it the second leading cause of lung cancer (Statistics Canada, 2016). This naturally-emitted soil gas enters buildings, typically by seeping in through foundations (WHO, 2009). Building design, extended winter, and geographical location expose residents to increased concentrations of radon gas (Eisinger, Simmons, Lammering, & Sotiros, 1991; Henderson, Kosatski, & Barn, 2012). Radon decay gives off tiny radioactive particles that, when inhaled, can cause mutation in DNA of lung cells eventually resulting in lung cancer (Gustavino, Meschini, Franzetti, Gratton, Allegrucci, & Sbordoni, 2014; Krewski et al., 2006). Women and children appear to be more strongly affected (Briggs et al., 2003), and the risk is up to threefold for smokers (Noh et al., 2016).

The National Radon Program (NRP) of Health Canada is responsible for raising public awareness through disseminating radon health risk messages (Health Canada, 2013). Despite multiple efforts, the program lags behind the desired public uptake. According to the latest national survey, 55% of Canadian households heard about radon, but only 6% of them tested for it (Statistics Canada, 2016). Similarly, a recent survey conducted in the national capital region in Canada, which is known for relatively elevated levels of radon, revealed that while 32% of those surveyed expressed some concern about radon health risks, only 12% tested for radon, and 3% took action to reduce the risks (Khan, Krewski, Gomes, & Deonandan, 2018). The gap between risk awareness and actual testing rates presents a challenge for public health professionals (Nicol, Rideout, Barn, Ma, & Kosatsky, 2015; Spiegel & Krewski, 2002).

In Canada, like many other countries, residents are responsible for radon testing and remediation (Health Canada, 2013; WHO, 2009). The guideline issued by the federal government is voluntary; it assumes that residents will act rationally according to the provided information (Health Canada, 2013). This assumption, however, has been challenged by previous psychological and preventive health research relating to health risk perception (Hevey, 2017; Rogers, 1983). Further, Spiegel and Krewski (2002), in a quantitative study, assessed the health risk perception of residents in high radon areas in Canada and concluded that the Canadian residential radon exposure guideline had not been effective at prompting homeowners to take action to reduce exposure.

The term 'risk' denotes the probability of experiencing a dangerous event and the magnitude of the consequences of that event (Aven, Renn, & Rosa, 2011). However, studies over the decades have provided convincing evidence that subjective public perceptions of risk differ significantly from the scientific evaluation of risk (Weinstein, 1988; Beck & Frankel, 1981; Janz & Becker, 1984). For example, in a high seismic zone, the risk that a resident will die in an earthquake may be mathematically lower than the risk of dying in a car accident. Yet, residents are comfortable with driving but panicked of the earthquake (Bayram, 2015). This is because residents do not mathematically or objectively calculate the risk. Slovic argues that no risk exists independently of human thoughts and culture (Slovic, 1992). Attempts to reduce health risks would benefit from an understanding of people's views. Research has identified that the success of any population-level awareness program is contingent on the views and actions of key decision makers at the household level (Lorang, 2001). Therefore, it is important to understand residents' knowledge and views of radon health risk.

Most studies that assess environmental health risk perceptions in Canada adopt quantitative approaches. To our knowledge, no qualitative study has been conducted that examines residents' knowledge and understanding of radon health risks, their views of enablers and obstacles to testing and mitigating, and their suggestions regarding how to improve the public's knowledge and action with respect to radon. Qualitative research enhances understanding of people's perceptions and experiences and is well suited to capture these views and their contexts in people's own words (Bourgeault, Dingwall, De Vries, 2010; Miles, Huberman, &Saldaña, 2014). It is important to achieve an understanding of residents' views. Therefore, this qualitative study focused on three research questions:

1) How do residents learn about radon and how do they view the risks associated with it?

2) What are the enablers and barriers to mitigation of the risk according to residents?

3) What suggestions do they provide to enhance information dissemination and protective action?

Methods

Sampling and data collection. This qualitative study follows a quantitative study we previously conducted with residents of the Ottawa-Gatineau area (Khan et al., 2018). In that study, we asked respondents to provide their email if they were willing to receive future correspondence; 286 individuals provided their email. Of these individuals, we purposefully selected 32 who had shown at least some background knowledge of radon. They included: homeowners and tenants; individuals who had tested and not tested homes for radon; and individuals with various educational and occupational backgrounds to ensure a maximum variation sampling. We also included in this study three interviews purposefully sampled for a pilot study on the same topic. In total, we conducted thirty-five interviews. Table 5 presents study participants' sociodemographic characteristics.

Table 5. Sociodemographic characteristics of participants.

Characteristics	Numbers	Percentage
Gender		
Female	8	23%
Male	27	77%
Age Groups		
18-44	7	20%
45-64	15	43%
65+	13	37%
Level of Education		
High School	3	9%
College	9	26%
Bachelor	11	31%
Graduate	12	34%
Total Household Income		
Less than $40,000	3	9%
Between $41,000-75,000	7	20%
Between $76,000-100,000	9	26%
Between $101,000-150,000	11	31%
Between $151,000 and Above	2	5%
Prefer not to Answer	3	9%
Homeownership		
Homeowner	29	83%
Tenant	6	17%
Language of Interviewees		
English	11	31%
French	24	69%

The interview guide included both closed and open-ended queries on sources of information on radon, views on radon health risk, and enablers and obstacles to taking action related to radon. We asked residents to provide suggestions on how awareness of radon health risks and actions to reduce such risk could be achieved. The first author conducted all the interviews, conferring periodically with the second author to update and discuss progress. All interviews were digitally recorded and then transcribed.

Ethical approval

Our research complied with Canada's Tri-Council ethics guidelines. The University Research Ethics Board approved the study protocol (H10-17-03). We secured informed written consent for participation, voice recording and direct quoting. We assigned a number to each participant to maintain anonymity and excluded any identifying information from the quotes.

Data analysis

We adopted an inductive approach to the analysis and focused on understanding issues from the perspective of residents. Following Braun and Clarke (2006) and Miles et al. (2014), after familiarization with the transcripts, initial codes that were close to the data were applied. The first author initially coded seven interviews, using descriptive codes. The process of coding was iterative: as this coding progressed, new codes were added, and some codes were modified. Following this step, the second author reviewed the coded interviews, and the two researchers developed a code list (Miles et al., 2014) that was used to recode the interviews. The first author then continued coding the other transcripts, while also convening with the second author on a regular basis to discuss emerging patterns in the data. These patterns or themes were developed in answer to the research questions. For example, initial descriptive coding indicated that some participants had learned about radon from newspapers, radio, TV and/or the internet. Each of these four had its own code, and these codes were then combined under the theme of "media sources," which was one of the themes helping us to answer the research question on sources of information on radon. Our final themes and sub-themes are presented in Table 6 below.

Table 6. List of themes and associated sub-themes.

	Themes	Sub-themes
1	Source of knowledge	Media Social network Education and occupation Home renovation shows Home inspectors The current study National Radon Program
2	Knowledge-risk awareness	Advanced Basic Deficient Faulty
3	Enablers	Understanding health risk (cognitive awareness) Concern for children and oneself (emotional awareness) Social influence (knowledge of significant others) Personalizing the risk Financial capability
	Barriers	Lack of awareness of health risk Cumbersome procedures Cost of remediation Tenancy Reduced property value (assumed) Voluntary nature of the guidelines
4	Residents' suggestions for improving knowledge dissemination and protective action	Role of public agencies Individual responsibility Shared responsibility Role of citizenry Incentivizing Mandating and legislating

Results

In this section, we report the results of our analysis of the sources of information and level of knowledge of participants. We then present participants' views of enablers and obstacles to testing and mitigation. This is followed by a summary of participants' suggestions regarding the ways to improve disseminating information and taking action to reduce radon harm.

1. Source of knowledge. We sought to understand how participants gathered knowledge on radon – what source of information and how they came upon it. We found that residents learned about radon through information gained from various media sources, the most common of which were various types of media such as newspapers, television, radio and the internet:

"There was a report in the Ottawa Residents, a local newspaper in the Kanata area" (SP19).

"I read something about it years ago, in the Maclean's magazine" (SP18).

"I watch television programs. When I was listening to the news, I heard them talk about radon" (SP20).

"I read some articles online" (SP22).

Other less common sources included one's *social network* of friends and clubs:

"We had friends who live a few kilometers from here, who told us about radon. This increased our awareness" (SP1).

"A lot of my friends used to work in Health Canada; I heard from them" (SP35).

"We were told in a geological club to be careful of some of the rocks… that one of the by-products of that was radon gas" (SP24).

A few participants mentioned their own *occupational education and practice* as sources of information:

"I was trained in hazardous materials operations; so, I came to know about radon gas" (SP32).

A few participants learned about radon in the course of considering *home renovation, construction or real estate transactions*:

“I first heard about radon about 15 or 20 years ago when I was planning to set up a marble countertop, and the marble countertop scheme was up” (SP18).

“Several years ago, I attended a home and cottage show here in Ottawa, and I had to stop in a stall that I believe was by the National Research Council. There I learned about radon. That was the first source of information about radon for me. I then looked through the internet. I read widely” (SP16).

A source of information that one would expect to be highly salient is *home inspectors* because these professionals are typically hired by new homeowners or residents to advise them on construction and other dwelling-related problems. However, only one participant mentioned this source of information:

“When we moved here, the home inspector mentioned that radon might be an issue in this area (Kanata)” (SP34).

Perhaps most alarming was the fact that several participants indicated that they learned about radon from the *current study*:

“I had not heard of radon till I was contacted to participate in your survey” (SP10).

“The first thing I heard about radon was your ad; from the links that you sent to me” (SP28); (please see recruitment ad in Appendix 27).

“I heard about it from your study” (SP25).

In sum, residents obtained information on radon from various sources, but this does not tell us whether the information they obtained and retained is accurate. We consider the

2. Level of knowledge and awareness of risk. Participants had different levels of knowledge about radon gas, its source and its potential effects; thus, awareness of risk varied across respondents. Some had very advanced knowledge and awareness of the risk, which was associated with their education or occupation. For example, the three participants below had backgrounds or occupations in biology, construction consultancy and engineering respectively:

“I have a biology background…I know how the situation can arise in a building, and what conditions generate the gas” (SP17).

“I have some knowledge about uranium degradation. In a climate such as this, the effects are worse in the winter because the house tends to be closed up… I think radon is quite serious as it is odorless, you don’t know about it unless you test for it, so it kills people silently, and that’s why it’s serious” (SP29).

“70 Bq (Becquerel) is equal to one X-ray. We had 280 Bq - that is equivalent of basically 4 X-rays in a year” (SP24).

Others’ advanced knowledge was based on their motivation to learn more about radon’s health effects in order to reduce the health risk. For example, a study participant stated:

“The best time to test for radon is in the winter when the doors and windows are kept closed. In summer, we usually keep our doors and windows open and so the gas does not build up. There is variation in radon release. It varies even on a diurnal basis. There are other factors that impact radon release, so it is good to test often, and even better to have a real-time detector if you have the capacity to buy one” (SP11).

Individuals with advanced knowledge also showed understanding of the synergistic risk associated with smoking:

“Radon is present everywhere. It is the level of radon that is harmful. You should know what the level is. If it is within the guideline level, then, we can say that there is not much harm to your health… If you have multiple potential risk factors for the same disease, such as smoking and radon in this case, then the combination of the effects is probably more than the effect from a single factor” (SP16).

Other participants had some basic facts, such as:

“I know it is a colorless, odorless gas, it seeps into the house through the basement, it is product of deterioration of uranium. It is naturally occurring, and it happens everywhere” (SP13).

However, other residents held views that were scientifically unfounded. Some of these views were that new houses are safe, that radon is not a problem in Ottawa, and that there is insufficient evidence on the harms of the gas:

“New houses have no radon: I suspect that my house does not have radon. Because of the age of the house – it is not ten years yet” (SP27).

“Houses built on clay, no chance of having radon” (SP26).

“It’s not a problem in Ottawa but in Winnipeg and Western Canada” (SP35).

“I don’t think there are sufficient studies to categorically say that this is serious enough” (SP20).

In sum, some of our participants did not actively seek information, and were rather passively exposed to it through the media or by hearing from colleagues, while others took a more active stance, seeking advanced information. Awareness of risk varied, and it is important to note that the knowledge retained by some residents is faulty and potentially harmful to their health.

3. Enablers and barriers. We asked participants about the factors that would facilitate or hinder radon testing and preventive actions. Enablers to taking protective actions included: having an understanding of the risk; being health conscious; being responsible for providing care for family and children; having knowledge of others who had contracted lung cancer; and having financial capability. The obstacles consisted of lack of awareness of health risk, cumbersome procedures, cost, lack of home ownership, concerns about reduced property values, and the voluntary nature of the guidelines.

Enablers. Most of the participants who indicated that they engaged in actions aimed at testing for radon levels and/or reducing the risk of radon showed a clear understanding of the risk (cognitive awareness) and had also concerns (emotional or affective awareness) regarding their family members' health – especially worries about children's health. These individuals were most motivated to take action.

"My daughter has been sleeping in the basement for thirteen years; I wanted to know whether she has been exposed to radon for this long time" (SP29).

"My son used to sleep in the basement from time to time" (SP32).

"My daughter does sleep there quite often; so, I am concerned about her sleeping in the basement and a buildup of radon" (SP23).

Attention to and concern regarding one's own health was also mentioned as an enabler:

"It's the concern about having lung cancer from radon. I am health conscious; if I know something is a risk factor, I would go for fixing that" (SP7).

"The desire to avoid any unnecessary health effects. There are health hazards while we drive on the highway and that's why you make sure that your vehicle is in good shape and you also put on seat belts. The same kind of thing applies here. If you are aware of the health hazards, you take the appropriate measures" (SP16).

"It was the concern about my health that encouraged me to test and fix the house for radon… I could not afford any more insult (exposure to radon) to my lungs" (SP24).

Knowledge of others who had contracted lung cancer seemed to influence some participants to take action. Specifically, seeing individuals who could be similar to oneself and who had contracted lung cancer, heightened risk perception (i.e. personalizing the risk through a vicarious experience):

"There is a man of 60 in my neighborhood who got lung cancer" (SP30).

"We have friends who live a few kilometers from here, who told me that he was concerned about his home and he tested… I was surprised because my son used to live in the basement and so my husband became concerned when he got the information" (SP1).

"I was watching a medical program on TV that was doing a feature about women and cancer, specifically lung cancer. The women in the program who got lung cancer did not smoke. They had a healthy lifestyle, they were fit, they exercised, but they still got lung cancer. So, the doctor was trying to find out –how was that possible? The cancer researcher, I don't recall his name, said that there is a high possibility that it was radon gas… So, they recommended to stay healthy, to take action, and directed to have the house tested to see if there was radon gas" (SP7).

Another enabler was financial capability. Given that residents typically bear the cost of testing homes and of mitigating for the potential harm, being financially capable appeared as an enabling factor:

"Certainly, it would be expensive for people who are not as fortunate as we are" (SP1).

"I don't think it is that much expensive, this is not a barrier for me" (SP2).

Barriers/challenges. Although none of the participants indicated that lack of awareness was an obstacle to taking action for themselves, most referred to this factor as a potential barrier for others to take action:.

"First is knowledge, if people don't know anything at all – it's the first challenge" (SP11).

"I think most people are not aware of what the indoor air quality is in a house" (SP21).

The cost of mitigation also came up as a barrier to taking action, especially with respect to reducing radon levels in a home, and less so, with respect to purchasing a monitoring device:

"There is always the finance involved because one has to bring in a specialist and it may cost up to $4,000" (SP7).

"I just cannot afford it" (SP20).

One participant spoke about the various procedures associated with testing as a potential barrier, indicating that the process may be cumbersome for some residents who might not have enough time or patience:

"Other things may be where to get the kit, not knowing how much it may cost and how to do the test. There are the procedures to place the test kit at a certain place and wait for over 90 days and then send it to the lab by mail and wait for the result. These all take time… It also requires the willingness to go ahead and follow through with all the steps till getting the result. Some people may not have that time and patience" (SP16).

Lack of home ownership – tenancy – was mentioned as a potential barrier:

"If I am a renter and my landlord is not aware of this problem, he may not do the test" (SP5).

"… for some, not owning the home - like tenancy, people who rent their houses" (SP15).

"If you are renting your house and do not own it, then it may be a challenge" (SP25).

Another challenge mentioned by homeowners was the difficulty in selling the house should radon levels be tested and found to be elevated:

"People may think that if radon is detected, it may be a problem in selling their houses. There is a stigma associated with this - that the house is contaminated. In areas where these types of contaminants are found, assessed property values tend to decrease" (SP24).

"…because otherwise, they lose the value once they are going to sell the house" (SP32).

Reference was also made to the voluntary nature of the guideline as a potential barrier for mitigation.

"If the building codes are voluntary and it costs even $100, nobody is going to do it as that means paying $100 from the builder's pocket. But if it is mandatory, then only it will be done" (SP32).

"I think almost everything that is voluntary is not going to motivate people to take action. If it's mandatory, then people will follow the guideline, even if they are not well aware of the issue" (SP33).

In sum, various enablers and barriers influence residents' action-taking with respect to radon.

4. Residents' suggestions for improving knowledge dissemination and protective action.

Given the limited information that some participants had - and the fact that some of the knowledge they retained was not scientifically-based and could potentially be harmful - we sought to understand participants' views of what should be done to raise residents' awareness of the health risks and encourage them to take action. We believed it was particularly important to obtain residents' views, given that there are national guidelines in place, yet these do not appear to be highly effective in educating the public or incentivizing it to take action (Khan, Krewski, Gomes, & Deonandan, 2018; Statistics Canada, 2016). This indicates that the program is poorly matched with most residents' needs for information and incentive. It was, therefore, particularly important to learn from residents what might be helpful for them.

We, therefore, asked participants to provide suggestions and recommendations on courses of action to help raise awareness and take action, and found out that the greatest majority of participants emphasized the role of public agencies. References were made to concerted action including *"the government at all three levels – municipal, provincial and federal" (SP15)* in disseminating information about the presence and health risks of radon, and to seeking participation from *"all the stakeholders who may be involved in this issue" (SP2),* including the government, the private sector (e.g. the homebuilders) and associations (e.g. the Cancer Society). The view was that this should be done through various media. Participants stated that a credible government body such as Health Canada should engage in effective publicity campaigns using print health education materials (such as pamphlets providing information) and audio-visual media such as TV. Some suggested specifically broadcasting through local news channels, and others suggested adopting a combination of approaches:

"In television, there should be an image of some of the effects of radon, and it will be easier for people to understand" (SP25).

"One option could be sending a flyer to the mailbox as the hydro company does for energy efficiency, could be a newspaper article, could be online, could be television shows…or it could be a mix of all these things as different people have different choices and means to get the information" (SP29).

The very few residents who focused on the role of the *individual* either referred to individual harmful behaviors or believed that the individual should take action after being informed by the government:

"Well, it could be the individual's problem, it depends on a lot of things like people's living habits. Some people smoke … that could contribute to that. So, this is an individual rather than an overall societal problem. In that particular case, the responsibility should go to the individuals, not to the government" (SP35).

"I think the responsibility goes primarily to the individuals. The government has the role of providing information, but it is the individuals who have to take steps to test and where necessary, to mitigate the issue" (SP16). These views were few in number.

Others indicated that "it is a *shared responsibility*" (SP34), stating that:

"It's a societal problem, not individual because it runs from coast to coast" (SP7).

"I think it is an overall social problem, as it affects the health of everybody" (SP30).

According to them, the governments should be responsible for informing people about the risk, but the individual property owners should take the initiative for testing, and where bearing the mitigation cost exceeds the financial capacity, one could seek support from the government:

"I think both have the responsibilities. Government can support, but homeowners should take the initiatives to do the test first" (SP11).

"The initiative should be taken by the homeowners; the government should be in support" (SP12).

There was also the suggestion that the use of celebrities may help drive the message more strongly:

"You can get help from David Suzuki; he would be the best person to communicate this message" (SP15).

Getting help from health clinics to disseminate the message was also offered as a suggestion: "The clinics can do this job by putting up signs that draw people's attention" *(SP1).*

Two participants emphasized the role of the citizenry and the communities in raising awareness through processes similar to social movements:

"It is not your issue or my issue, it is everybody's issue, and we have to get together to stop this from happening" (SP20).

"People from the radon-prone areas should come forward" (SP13).

Suggestions regarding actions aimed at testing and/or mitigating were framed in terms of incentivizing and/or legislating procedures. For example, some participants stated that providing free test kits, tax rebates and subsidies would encourage some residents to take action given that "most people are not going to pay for the test. If someone has a minimum wage and you think he is going to test and fix his house by himself- it's not going to happen" (SP27).

While these suggestions address incentivizing procedures, other suggestions focused on legislating and setting mandatory requirements. A few suggestions centered around making testing mandatory, though it was also recognized that this might be difficult to achieve. Other areas where government legislation was seen as more effective was in terms of setting building codes:

"The government needs to put in place building codes -every house built in such a way that a minimum requirement has to be met to prevent radon gas" (SP24).

"If there are CO (Carbon Monoxide) and smoke detectors in houses, why not a real-time radon detector?" (SP30).

Participants also suggested legislating real estate transactions and including a mandatory provision for property sellers to declare the radon status during all real estate transactions: "Testing and disclosure – both should be made mandatory" (SP34).

"I would be very upset if I find after the fact that there is radon in the house. I think it's reasonable to have a clause in the sale agreement" (SP32).

Thus, the recommendations focused mainly on the role of public agencies in disseminating information, and in incentivizing or mandating action through more stringent regulation.

Discussion

The objectives of this qualitative study were to gain an understanding of residents' knowledge and perceptions of the risk associated with radon, to identify the enablers and obstacles to taking action, and to obtain their suggestions regarding how knowledge and action associated with radon can be improved. The results showed that residents acquire knowledge passively or actively from diverse media sources, their social network, their education and/or occupation, home shows and home inspectors. Most surprising was the fact that several residents came to know about radon for the first time from the current study. This supports the findings of our preceding study (Khan et al., 2018) and the conclusions of previous studies that the Canadian National Radon Program has not been highly effective in informing residents and in prompting action to reduce radon exposure (Spiegel & Krewski, 2002).

While most of the residents had basic knowledge about radon, a few demonstrated in-depth knowledge. However, an important result from this study is that some residents have misconceptions about radon, showing what has been termed unrealistic optimism, which involves individuals holding an unreasonably low estimate of their own susceptibility to the risk (Weinstein, 1988). Studies in the US (Beck & Frankel, 1981) and Ireland (Clifford, Hevey, & Menzies, 2012*)* have demonstrated that it is not uncommon for individuals living in high radon areas to underestimate the potential harm or to believe that radon is a threat to others but not to themselves.

Among the accounts from participants were references to a 60-year old neighbor, and to women in a TV show who were otherwise healthy and non-smokers, and who had contracted lung cancer. The availability of examples of harm may allow one to form a judgment that radon poses a health risk (Hevey, 2017). Still, caution should be taken in assuming that merely being exposed to the risk information can lead to the formulation of appropriate conclusions or to taking appropriate action. Researchers (Weinstein, 1988; Weinstein, Sandman, & Robert, 1991) have shown and argued repeatedly that information processing and behavior are highly complex and are influenced by multiple factors at various levels. For example, Weinstein et al. (1991) stated that “an intervention capable of having a major impact on perceptions of risk may have to confront directly the mini-theories people construct to justify their optimism” (p.32), thus pointing to *micro-level* factors. The authors note that such interventions would be challenging to implement on a large scale given the various mini-theories that people construct (Weinstein et al., 1991). Specifically, in our study, the findings show that associating radon health risk with both personal (e.g. diagnosis of lung cancer) and family members’ (especially children’s) health appeared as an impetus for residents to test, mitigate and continuously monitor radon level. These are examples of events and occurrences that positively helped to shape individuals’ mini-theories.

The presence of such mini-theories suggests that the more varied the media, the more diverse the types of messages (e.g. cognitive and emotional appeals), and the more agencies delivering the message (e.g. different levels of government, associations, health clinics), the higher the likelihood that knowledge and action regarding radon will increase. Studies in the UK have shown similar results where multiple radon health risk communication campaigns effectively raised awareness (Poortinga, Bronstering, & Lannon, 2011) and health communication messages from authentic sources had positive effects especially in radon-prone areas (Poortinga, Cox, & Pidgeon, 2008).

As we have pointed out, risk perception is a subjective phenomenon. It is influenced not only by micro-level factors such as individual mini-theories and information processing but also by the macro-level context (Wang, Ju, Stark, & Teresi, 2000). At a *macro-level*, we encounter the social context of radon threat, where views of risk and of who is responsible for reducing the risk are influenced by the community or social framing of the issue (Wang et al., 2000). For radon, there is no collective community action built through consensus, and therefore, individuals show various views. Whereas some established social norms, consensus and groups (as on gun control in the US) can motivate people to act, the absence of such a community movement influences inaction even in high radon areas (De Wit, Das, & Vet, 2008). In this vein, a few participants in our study called for residents to get together and to engage in collective action on the issue.

Another macro-level factor of relevance in interpreting the results of our study is that the health care system in Canada is publicly-funded and highly regulated. Federal, provincial and municipal government bodies have extensive regulations associated with various health risks. This helps account for residents' views regarding the role of government in managing radon risks. The majority of participants viewed government as the primary actor with responsibility for informing the public and for incentivizing and mandating action to reduce radon risks. This points to the critical role that health policy can play in reducing risks.

The suggestions we received from the participants pointed to the need to involve various public and non-governmental agencies, various types of messages, and various incentivizing and regulatory steps. This is particularly important because research has shown that simply providing information is not sufficient (Witte, 1992). For example, evidence has shown that when a health message is personally significant, people try to moderate the seriousness of the health risk, raise questions about the accuracy of the risk information, and process it in a subjective manner (De Wit, Das, & Vet, 2008; Kunda, 1987; Liberman & Chaiken, 1992).

The primary audience of radon messages is the at-risk population who live in an area with high levels of radon. This segment could be challenging to persuade because they might process the information defensively when it is too intimidating (Liberman & Chaiken, 1992). Defensive techniques include, for example, avoidance of message (Donohew, Lorch & Palmgreen, 1991) and denial of susceptibility (Kunda, 1987). However, there is also evidence showing that individuals' motivation for action is driven more by the emotional aspects of perception than by cognition (Khan et al., 2018; Tversky A, Kahneman, 1981; Witte, 1992). These various considerations reinforce the importance of using different approaches and messages.

Our study did not gather systematic information from participants about the content of messages on radon that they would find to be effective, as this was outside the scope of the study. However, some of the participants' accounts indicated that the content is important. In fact, some research has indicated that individuals are likely to feel more threatened by a description that assigns active rather than a passive agency to radon e.g. ‘radon gas invades your home’ as opposed to ‘radon gas seeps into homes’ (Dragojevic, Bell, & McGlone, 2014). Therefore, studying residents’ views of message content would help improve communication campaigns on radon.

Limitations

A limitation is our inability to generalize from the current study to the population at large; however, this is a typical feature of qualitative studies (Bourgeault, Dingwall, & De Vries, 2010). In fact, exploratory qualitative studies are not intended to provide generalizable data, but to enhance understandings that can be further tested in broader-based quantitative studies. Our study was also limited in number of participants and locations; included former or current employees of the federal government who were likely more exposed to advanced radon information. Future research would benefit from interviewing more diverse participants and in other cities to generate additional insights. We believe that studies in cities where there have been condensed and concerted efforts to communicate with residents and incentivize action would provide an interesting extension of or counterpoint to this study.

Conclusion

This study sheds light on the vital topic of residents’ knowledge and views of radon and its risks. To date, studies on views of radon risk in Canada have tended to adopt quantitative approaches. The value of the qualitative approach is that it provides a deeper look into participants’ experiences, thus, provides information to complement quantitative results. Our study showed that many people do not get the crucial information on radon and some retain misconceptions about the health risks even after being exposed to information. Many residents report barriers in testing and engaging in protective action, even after receiving the pertinent information.

Our study underscores the importance of seriously considering how radon risk is understood and dealt with by residents. We identified that mere cognitive risk awareness is not enough; additional emotional awareness motivates residents to take action regarding testing and mitigating their houses for radon. Therefore, radon health communication will be more effective when programs address both these aspects of risk perception using different media, diverse modes of delivery by varied agencies and organizations along with plausible regulations and incentives, where necessary. Future research can explore the dual aspects of risk perception and thus help to develop tailored risk communication messages capable of motivating residents to mitigate their homes for the health risk from exposure to radon.

Abbreviations:

NRP: National Radon Program

SP: Study Participants

Declarations:

Ethics approval, consent to participate and publication: Our research complied with Canada's Tri-Council ethics guidelines. The University Research Ethics Board approved the study protocol (H10-17-03). We duly secured informed written consent for participation, voice recording and direct quoting.

Consent for publication: Both authors agreed with the final manuscript and gave consent for publication.

Availability of data and material: Available from the corresponding author on reasonable request.

Competing interests: The authors declare that they have no competing interests regarding this research and publication.

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Authors' contributions: Both the first author and the second author designed the study, developed the concept and co-analyzed the data. The first author conducted interviews and drafted the manuscript. The second author critically reviewed and revised the paper. Both authors read and approved the final manuscript.

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Chapter Seven: Systematic Review of Radon Intervention

The fourth paper of this thesis was a systematic review conducted under direct guidance of Dr. James Gomes and with technical support from Dr. Daniel Krewski. The article has already published in an Elsevier journal Heliyon on May 27, 2019. A copy of that manuscript is presented here.

Systematic Review Article:

Radon Interventions Around the Globe: A Systematic Review

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Systematic review registered with the National Institution of Health Research, UK.
Registration number: CRD42018110016

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Abstract

Background: Radon is the primary source of environmental radiation exposure posing a significant human health risk in cold countries. In Canada, most provinces have revised building codes by 2017, requiring construction solutions to avoid radon in all new buildings. While various construction solutions and remediation techniques have been proposed and evaluated, the question about the best method that would effectively reduce radon in a variety of contexts remained unanswered. Radon practitioners, officials of radon control programs, and businesses offering radon testing and mitigation services, builders, property managers, homeowners and residents also have similar queries. Objective: This paper systematically reviewed both experimental and observational studies (S) with radon interventions (I) used globally in residential houses (P) compared to other residential or model houses (C) to evaluate relative mitigation effectiveness (O) that could guide selecting the best radon reduction strategy for residential buildings.
Methods: Two researchers searched fifteen academic bibliographic and grey literature databases for radon intervention studies conducted around the world, with particular emphasis on areas of North America and Europe published from 1990 to 2018. Radon interventions in residential and model houses were included, but studies piloted purely in the lab were excluded; the PRISMA checklist used to synthesize data; Cochrane and Hamilton tools used to evaluate study quality.
Results: Studies around the globe have investigated a variety of construction solutions, radon mitigation and remediation systems with different levels of effectiveness. In most cases, sub-slab or sump depressurization system (SSDS) with active ventilation technique was found more effective in achieving a significant and sustained radon reduction than the passive methods such as sealing, membrane, block and beam, simple ventilation, or filtration. The choice of an optimal strategy largely depends on the factors related to the initial radon level, routes of entry, building design and age, as well as other geologic, atmospheric, and climatic conditions.
Conclusion: Although an active SSDS is the best mitigation systems, at places, it needs to be combined with another system and installed by a trained radon professional considering the pertinent factors to ensure radon level continues to remain below the action level. This study did not conduct any economic evaluation of the mitigation measures. Future review with studies on the implementation of new building codes will provide updated evidence. Recommendation: For the practical implementation of radon mitigation, training of the construction industry, information provision for residents, the establishment of public funds, incorporation of radon-prone areas in the land utilization maps, and enacting building codes deemed essential.
Keywords: Radon; Intervention; Mitigation; Depressurization; Effectiveness.

Graphic Abstract

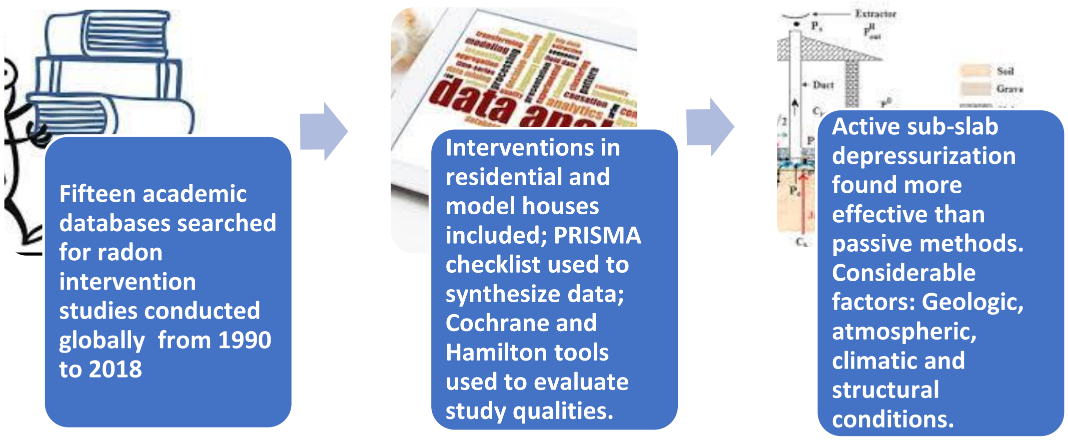

Figure 12. Graphic Abstract: Systematic Review of Radon Interventions

Highlights

- Radon is the primary source of environmental radiation exposure posing a significant human health risk in cold countries, particularly in high radon areas.
- This paper systematically reviewed radon interventions used globally in both new and existing residential houses
- Studies around the globe have investigated a variety of radon reduction systems with different levels of effectiveness.
- In existing houses, sub-slab or sump depressurization system (SSDS) with active ventilation technique was found more effective in achieving a significant and sustained radon reduction than the passive methods; whereas construction solution with barrier membrane along with SSDS found to do the same for new houses.
- The choice of an optimal strategy largely depends on the factors related to the initial radon level, routes of entry, building design and age, as well as other geologic, atmospheric, and climatic conditions.

Radon Interventions Around the Globe: A Systematic Review

1. Introduction

Radon (Rn^{222}) gas is a product from the decay chain of uranium (U^{238}), originates from Ra^{226} (Radium) and enters buildings mainly through the porous basement foundations (WHO, 2009). Both the World Health Organization (WHO, 2009) and the International Agency for Research on Cancer (ICRP, 2007) identified radon as a category one human carcinogen. The universal outdoor radon concentration is between 5 and 15 Bq/m^3, and it does not pose any health risk (WHO, 2016). However, the short-lived radon progenies (P^{218}, Pb^{214}, Bi^{214}, and P^{214}) can accumulate in closed spaces (mines, caves, indoors) and emit radioactive alpha particles that upon inhalation remain in the lung tissues and mutate DNA to cause cancer (Gustavino et al. 2014; ICRP, 2007).

Although radon has been known for over half a century and responsible for about 15% lung cancer deaths globally (WHO, 2009), until recently a few countries have taken constitutional action to address the threat. As per the International Residential Code (2017), an effective radon control method should be in place during all new constructions, particularly in areas where radon level is frequently found high. The Council of the European Union (2013) enacted the *Basic Safety Standards Directive* in 2013 that requires member states to address the radon issue by developing action plans. Many European countries and most states of the USA have adopted buildings codes conforming to the international standards (National Conference of State Legislatures, 2015).

Canadian federal government has a model national building code that provides broad policy direction with no legal status (National Research Council Canada, 2017). However, it becomes an act once accepted by the provincial and territorial governments (Canadian Environmental Law Association, 2017). Most provinces and territories (except Ontario and Quebec) of Canada revised the building codes by 2017 where builders require construction solutions to avoid indoor radon in all new dwellings (CELA, 2017).

Despite these updated building codes and free, accessible handbooks and guidelines, homeowners of existing houses in most countries do not require to test, mitigate (to reduce the exposure in existing homes by applying various temporary methods) and remediate (to install a systematic technique to sustainably reduce exposure to radon below the reference level) radon. They do not also need to declare the radon status of properties during the real-estate transaction. Consequently, recent studies in Alberta found an average of 31.5% higher radon level in the new houses compared to the existing ones built before 1992 (Stanley et al., 2017). Thus, many informed citizens enquired about the best mitigation system and the optimal time to test and install that. Radon practitioners, officials of radon control programs, and businesses offering radon testing and mitigation services, builders, property managers, homeowners and residents also have similar queries regarding the implementation of building codes for different types of houses and geographical locations. Studies around the world have been evaluating the effectiveness of active (that uses an electric fan), passive (gets benefit only from natural ventilation) as well as other mitigation techniques in combination for decades. However, the question about the best mitigation system that would work in a variety of contexts remained unanswered. By the best method, we meant the one that can effectively and sustainably reduce radon below the reference level; it is also cost-effective, less disruptive to install, feasible for the majority of dwellings, and easy to maintain. In this review, we mainly focused on the overall effectiveness of the radon control systems.

We conducted a systematic review of both experimental and observational studies (S) with radon mitigation interventions (I) in residential houses (P) of countries around the world, with a focus on areas of North America and Europe that have cold climates and similar construction practices to Canada. The interventions were compared to the ones installed or conducted in the residential or model houses (C) to evaluate the relative radon reduction effectiveness (O) that could guide selecting the best mitigation strategy for residential buildings in Canada and beyond. The objective of this systematic review was to answer the following research questions:

a) What is (are) the most effective radon control system (s) in terms of reducing radon below the action level in both new and existing houses?

b) What is the best timeline to test and install the control system(s) in the new and existing residential houses?

c) What factors are worthy of consideration while planning for controlling radon in a house?

2. Methods

2.1. Protocol and registration. A systematic review protocol was developed and registered with the National Institution of Health Research, UK. The registration number and link: CRD42018110016

2.2. Eligibility criteria. This review of evidence on the effectiveness of radon interventions did not involve human subjects. We selected both experimental and observational studies with radon interventions. Geographically, we included studies mainly from Europe and North America but also considered suitable studies conducted in other cold countries. We included only the residential and experimental model houses but excluded studies reporting only indirect experimental measures of effectiveness in pure laboratory settings. The selection of literature was limited to English language and medical, public health disciplines but excluded studies conducted under all other disciplines. The selection was not limited by the publication status and included studies conducted between 1990 and 2018.

2.3. Information sources. Fifteen academic bibliographic databases (Academic Search Complete, ACCESS Digital Library, Avery Index, CAB Abstracts, CINAHL, The Cochrane Library - OVID & Wiley, EMBASE, Erudite, Geobase, Global Health, IBSS, PubMed- Medline, PAIS, PsycINFO, Web of Science) and grey literature (government survey report, other data or systems' reports from the WHO, ICRP, EPA, EU etc.) were searched for radon intervention studies and related documents published from 1990 to 2018. Additionally, reference lists of the selected articles, textbooks were searched; radon researchers and experts were requested for any relevant documents. The last search was made in December 2018 to supplement the review with the most recent contents.

2.4. Search strategy. Two researchers independently searched electronic databases, screened and critically appraised studies following the search criteria using Medical Subject Headings (MeSH) with help from a librarian at the University of Ottawa. MeSH words included 'Radon,' 'Testing,' 'Retesting,' 'Intervention,' 'Mitigation,' 'Depressurization,' 'Sump,' 'Barrier,' 'Membrane,' 'Ventilation,' 'Air Cleaner,' 'Radon Well,' 'Effectiveness', 'Time,' 'Factor,' 'Geology,' 'Climatic,' 'Atmospheric,' in various combination of search. An example of the search strategy applied by Dr. James Gomes on Thu June 2, 2017, at 17:23:56 in PubMed was: (((((radon) AND (intervention) OR (Remediation) OR (mitigation) OR (assessment) AND (Depressur*) OR (Sump) OR (Barrier) OR (Membrane) OR (Ventilation) OR (Air Cleaner) OR (Radon Well) AND (effectiveness) [ptyp])))))

PubMed Results

Items 1 - 115 of 115 (Display the 115 citations in PubMed). The limits put were peer-reviewed articles and period of publication from 1990-2018.

2.5. Study selection. Sixty-six documents were included for the final review: 53 peer-reviewed articles and 13 other types of documents (Figure 13. PRISMA Flow Chart: Systematic review below). Among the 53 peer-reviewed articles, 15 were on radon remediation interventions that were thoroughly reviewed (Table 7 below), and data extracted. Other 38 documents related to the factors that affect radon mitigation and relevant information. Among the 15 articles, six were experimental (high quality), four quasi-experimental (moderate quality), and five quantitative comparative studies (moderate quality). Among the 38 relevant articles, 11 were experimental (high quality), three reviews (high quality), and 18 quantitative studies (moderate quality). Besides, there was one case-

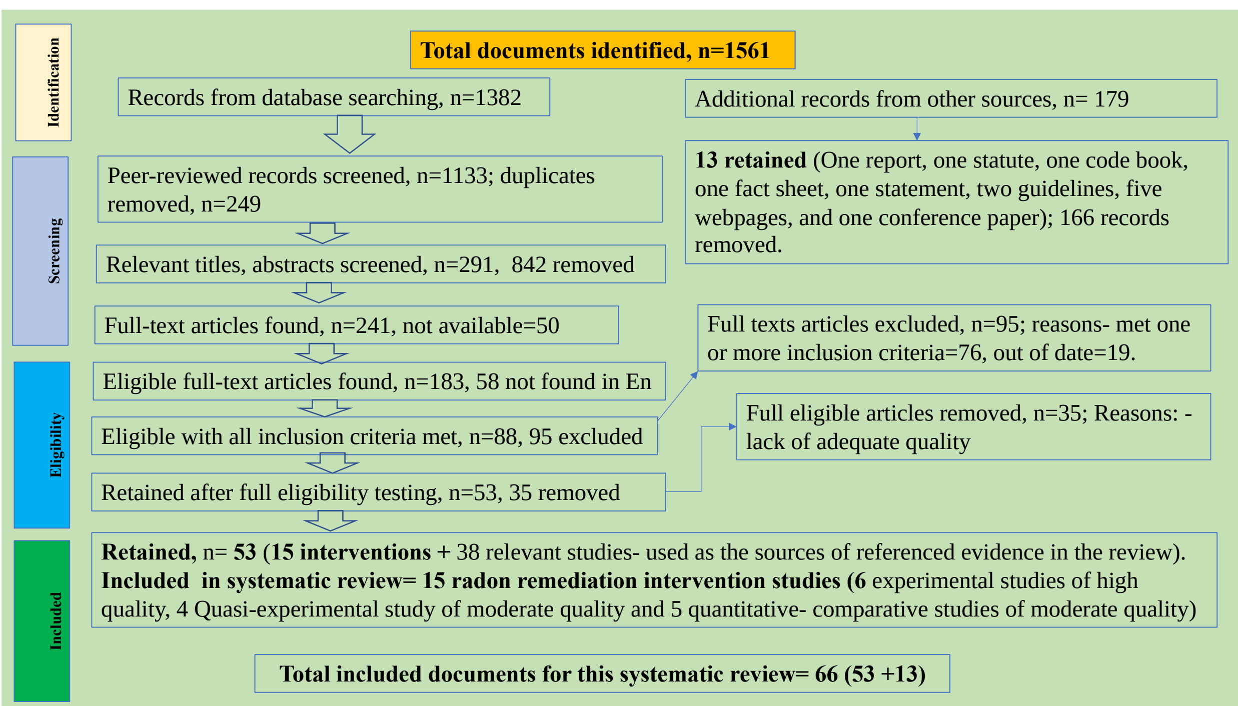

Figure 13. PRISMA Flow Chart: Systematic review

-control study, four case studies, and one qualitative study. All of these studies including the qualitative article were of high quality. As mentioned above, variations of measures made very little quantitative synthesis possible; thus, the synthesized data were not suitable for meta-analysis. The disparities remained even after grouping up the interventions and outcomes; so, the data were summarized narratively.

2.6. Data collection process. Two researchers extracted data independently but met regularly to discuss findings, compare the outcomes of search, and agree with consensus about the inclusion of documents in the review based on the review protocol developed earlier. Data were then, collated in a single spreadsheet. The PRISMA 2009 checklist was followed to synthesize data. Quality of the experimental studies and uncontrolled studies was assessed by using the Cochrane risk of bias tool and Hamilton tool respectively. The criteria for quality at the study level was measured with the existence of a suitable comparison group and at the outcome level with the reliability and validity of the data for each important outcome by identifying the methods employed to assess them in each study (Moher et al., 2009).

2.7. Data items. The article-wise data were listed under sub-headings of background, objective, method, measures, intervention, outcomes, limitations, conclusion, recommendation and applicability. The outcomes were defined as effectiveness of the mitigation technique in terms of percent reduction of radon level after mitigation compared to the pre-mitigation level of radon in the intervention and control houses across the studies conducted in different countries. The assumption was that every mitigation technique would reduce radon level at a certain level that was simplified to express in percentage whatever unit of measurement a study might have used.

2.8. Risk of bias in individual studies. The study design was assessed to determine the risk of bias of individual studies and the reliability and validity of the data were evaluated for each important outcome by identifying the methods employed and analyses used to assess the outcomes. Both study and outcome level information was used in synthesis.

2.9. Summary measures and synthesis of results. As the effectiveness was presented in percentage without always mentioning the means and confidence intervals, the principal summary measures could not be estimated.

2.10. Risk of bias within studies. The intervention studies conducted from 1990 till 2018 were selected whereas most of the provinces/territories of Canada adopted or revised building codes by 2017, thus, there remained a publication bias that may affect the cumulative evidence. As the focus was on the effectiveness of radon mitigation, only the selected parts of study findings that dealt with this aspect were retained leaving all others. However, this has not affected the cumulative evidence on the effectiveness of radon remediation. Besides, there is a possibility that some studies, typically those with positive ('statistically significant') results, are more likely than others to be published and therefore included in the review.

2.11. Risk of bias across studies. After assessing the individual study, the bias across the studies was evaluated. The risks of bias in the included studies from publication, selection and reporting aspects are described in the discussion section of the review.

2.12. Additional analyses. Other related factors that influence radon mitigation are narratively described. No further analyses such as sensitivity or subgroup analyses were conducted due to the lack of adequate numeric data. No meta-regression was also done due to lack of homogeneity of the study protocols, measures and outcomes across the selected studies.

3. Results

3.1. Synthesis of results. The data from fifteen selected articles are synthesized in Table 7 below. These are followed by the narratives that answered the research questions. PICOS format was followed for the synthesis of most relevant articles with citations in the first column.

Table 7. List of Selected Studies of Radon Mitigation Intervention with Relative Effectiveness

Study Design, Citation, location	**Population, Sample, Measures, Duration of follow up/ Timeline**	**Interventions, Comparison**	**Baseline Radon Before Mitigation (Bq/m^3)**	**Outcome After Mitigation (Bq/m^3)**	**Effectiveness***
Quantitative -comparative study by Stanley et al., 2017 in Calgary, Canada.	2382 residential homes tested for radon for at least 90 days (median 103 d) between 2013 and 2016. High radon level homes were remediated and retested to determine the efficacy of radon reduction techniques.	Sub-slab depressurization mainly but in a minority of cases, radon-impermeable membrane installed.	Average 126 (range >15 - 3441); 1135 homes had >=100; 295 homes had >= 200; 90 homes had average 575.	Mitigated 90 homes with av. 575 radon and noted reduced av. levels of 32.5. The house with the highest radon level of 3441 was reduced to 86	Highest mitigation efficacy recorded was 97.5%; Mitigation was effective in reducing radon levels to below 100 Bq/m^3 in all cases and typically reduced levels by 92%.
Experimental study by Boardman & Glass, 2015 in Wisconsin, USA	A single-zone air infiltration model was calibrated to measure tracer gas, soil moisture, and air exchange rate.	Active soil or sub-slab depressurization system (AS/SSDS)	321.9 ±5.18	11.1± 7.4	96.5% efficiency in radon reduction; >75% reduction in moisture
Quasi-experimental study by Brossard et al., 2012 in Canada.	Mitigated nine houses by installing SSDS with two types of discharge and fan locations: Basement or roof-discharge.	Sub-slab depressurization systems (SSDS) with fans at two levels	322-1931	<15 to 196	91+_6% at ground level and 94+_5% at the attic level
Quasi-experimental study by Brossard et al., 2015 in Quebec, Canada.	Above ground level (AGL) discharge with the fan located in the basement and above roof line (ARL) discharge	Sub-slab depressurization systems (SSDS)	Above 300	ARL (Avg%, SD)=75.3 ± 13.6; and AGL=74.3 ± 20.8	ARL 89%, AGL 95%.

	with the fan located in the attic.				
Quantitative -comparative study by Groves-Kirkby et al. 2006 in Northamptonshire and neighbouring counties, UK.	After measuring radon levels, 73 post constructed houses remediated with fan-assisted sump pump and compared with 64 houses remediated during construction with protective radon membrane only.	Fan-assisted sump-pump and protective membrane used as damp-proof; included a cavity tray to seal the membrane together with weep-holes in it for drainage.	Post-construction houses : 516; During construction houses: 458	Post construction houses: 60; During construction houses: 107.	With active sump-pump 100% and with protective membrane only 89%
Quantitative -comparative study by Groves-Kirkby et al. (2008) in the UK	Radon concentration data collected from 170 homes situated in Radon Affected Areas in Northamptonshire and neighbouring counties.	Conventional sump-pump technology by a commercial organization	487.6	64.6	100% of remediated homes achieved reduction to below the Action Level of 200 Bq/m^3 and more than 75% of the sample exhibiting mitigation factors of 0.2 or better.
Experimental study by Marley, 2001 in Northamptonshire, UK.	Studied four model single story buildings with construction design similar to local houses.	Air-Conditioning (AC) and Central Heating without AC	96-1083	Much lower than the UK action level of preceding level.	40-100%
Quantitative -comparative study by Long, 2013 in three counties of Ireland.	Radon level tested in houses of North Cork (n=152); South and West Cork (n=105) counties.	Homes exceeding the reference level remediated with active sump technique.	North Cork: Max 3300; 126 houses >200; 26 houses > 800. South and West Cork: Max 1000; 105 houses >200 and 3 houses >800	<200	92%
Quantitative -comparative study by Huber et al., 2001in western Tyrol, Austria,	Five years after mitigation, five different remedial actions were examined in five houses for their efficiency	House 1: A mechanical intake and outlet ventilation with heat exchanger combined with a SSDS. House 2: SSDS with two	25,000	1,200	50 to 95%

		fans and loops of drainage tubes to withdraw radon from the area below the floor. House 3: A multilayer floor construction, with a fan to suck radon from a layer between bottom slab and floor. House 4: A basement sealing. House 5: A waterproof basement.			
Experimental study by Maringer et al., 2001 in the federal state of Upper Austria.	Studied 5 houses in high radon; for the first time used an extended Blower Door method to determine building tightness and radon levels.	Two farm houses mitigated with active SSDS and a single-family house mitigated with passive SSDS	Radon level varied from 150 to 900 (Avg. 457) depending on location and seasons	48 and 233	90% and 50%
Quasi-experimental study by Paridaens et al., 2005 in Belgium	A house in radon prone area with very high indoor radon concentrations was identified with passive measurement.	Active sub slab depressurization with a radial fan.	1790	<200	90%
Quasi-experimental study by Vázquez et al., 2011 in Spain	Evaluated four construction models in two locations (underneath the basement slab and outside the foundation wall) and two ventilation (natural and forced) techniques studied for no less than one month.	Sump depressurization with passive and active ventilation	Same for all 4 models: Basement 39400 and ground floor 6860	Combination 1 (C1): 1740 and 603; C2: 16600 and 3210; C3: 409 and 368; and C4: 327 and 480.	93-95%

Experimental study by Akbari & Oman, 2013 in Stockholm, Sweden.	A two-storey house renovated to conserve energy; a multizone dynamic simulation model developed using an Indoor Climate and Energy (ICE 4.0) tools and validated using measurements of energy for heating, ventilation and total energy use.	HRV (Heat Recovery Ventilator)	3582	27 (at the highest HRV performance level)	Almost 100% radon mitigation with 74% energy saving
Experimental study by Yasuoka et al., 2009 in Kobe, Japan.	In a 5th floor apartment having high radon concentration from the building material was tested for radon. Mitigated for radon with and without using the air cleaner as the case and control case.	Mitigated with two types of radon filters: a high efficiency particulate air filter (HEPA-filter) and a deodorizing activated carbon (carbon-filter).	Mean radon concentration, EEC and EF were 86±10 36±4 and 0.42, respectively.	In both cases reduction of radon (<15) was significantly lower (0.01 and 0.05 level)	Effective 95-99%
Experimental by Gao et al. (2008) Hong Kong, China.	Anti-radon coating was experimented in a newly constructed building.	Anti-radon coating for radon mitigation	Maximum and average radon level 130,000 & 86,000; and 100,000 & 63,000 for the case & control	Below the set action level 142 & 174	99.85%,

*Measured as the percentage of difference between pre- and post- remediation radon level

Studies conducted around the globe employed diverse techniques to remediate indoor radon in both experimental model and residential houses. Table 8 and Table 9 below show the comparative effectiveness of different remediation systems and construction solutions used in the existing and new houses respectively. Appendix 29 presents a country-wise summary of radon mitigation methods showing varying degrees of effectiveness. Based on these review findings, the research questions are answered in the next section.

Table 8. Comparing Effectiveness of Different Radon Remediation Methods in Existing Houses

Systems	Methods	Effectiveness
1. Depressurization		
a) Sub-slab depressurization (SSDS)	Vent pipes made of polyvinyl chloride are placed into the soil underneath the foundation. Air containing radon moving through the pipes is drained actively exterior to the building with an exhaust fan set at the garage, outdoors, or in the attic.	The most effective radon mitigation recorded in Calgary, Canada (Stanley et al., 2017) was 97.5%; previously the effect noted in Quebec by Brossard, Ottawa, Falcomer, & Whyte (2015) was 95%. Whereas in the USA (Boardman & Glass, 2015) the highest record was 96.5%. In Austria, radon mitigation using the same methods with active and passive ventilation system shown 90% and 50% effect respectively (Maringer et al., 2001)
b) Sump depressurization	A form of SSDS, where the sump pump used to drain water is capped and made to serve as a passage to move out radon containing air.	Effectiveness recorded in both Spain (Vázquez, Adán, Quindós Poncela, Fernandez, & Merino, 2011) and in the UK was almost perfect (99 to nearly 100%) with active ventilation (Groves-Kirkby et al., 2006).
c) Sub-membrane depressurization	A polyethylene barrier membrane used to cover the dirt floor at crawl space; thus, the sealed foundation prevents radon entry. A vent pipe is placed in the crawl space to draw radon-containing air and exhausted with a fan to the outside.	Effectiveness noted was 53% only with the membrane but once an active vent pipe depressurization added with the exhaust fan; effectiveness raised to 98% in the UK (Scivyer, 2001). Studies in Austria, the USA, Hong Kong and the UK supported these findings (Ennemoser et al., 1995; Henschel, 1994; Gao et al., 2008; Scivyer, 1993).
d) Block wall suction, another type of SSDS.	Fan and ductwork used to draw suction on the hollow interior cavities of a concrete block wall. It keeps the inner air pressure lower than that in outside; thus, draws radon gas from the soil and expel out before entering the house.	Studies in Austria found 50 to 99% effect in radon reduction with the block wall suction (Ennemoser et al., 1995)
2. Ventilation		

a) Active Ventilation	With an active air exchange (by fan, air conditioning, heat recovery ventilators) indoor-outdoor pressure gradient is created.	Moderate effectiveness (25-75%) noted in the USA (Henschel, 1994), UK (Groves-Kirkby et al., 2008; Marley & Phillips, 2001; Naismith, Miles, & Scivyer, 1998; Wang & Ward, 1997), and Norway (Rydock, Naess-Rolstad & Brunsell, 2002).
b) Passive ventilation	Air exchange between indoor and outdoor is increased by keeping the windows and doors open.	In Finland, passive ventilation is considered when winter radon level remains <400 Bq/m^3 (Valmari et al., 2014). Less effective results with variability noted in the USA (Henschel, 1994) and Austria (Huber et al., 2001).
3. Other		
Filtration: HEPA (high efficiency particulate air) filter and HEPA with deodorizing activated carbon-filter	Both filtration methods (HEPA and carbon filters) act as air cleaner and can filter out radon progenies that are measured as a decrease in radon equilibrium equivalent concentration (EEC). In the control case, the experiment was conducted without using the air cleaner.	In Japan, the calculated effectiveness of decrease in radon EEC found significantly ($p < 0.01$) lower with both filters compared to the control cases; though health risk remained unclear due to the increase in unattached radon EEC fraction (Yasuoka et al., 2009).
Mechanical supply and exhaust ventilation (MSEV) with heat recovery compared with Mechanical exhaust ventilation (MEV) & Natural ventilation (NV)	In Finland, impact of ventilation on the indoor radon level was assessed through an analysis taking into account the height and volume of the house, natural pressure difference, infiltration and mechanical ventilation rate noted in houses with NAV, MEV and MSEV strategies.	Regression analyses of radon concentrations with these strategies showed MSEV to markedly reduce pressure differences and radon concentrations by 30% in typically airtight apartments compared to the MEV and NV. They also noted radon concentrations 30 % lower in the two-story houses than in single units (Arvela et al., 2014).
a) Sealing (alone)	Sealing of radon entry points in floors and walls of buildings by impermeable filler and sealants	Least effects (0-40%) noted in the UK (Naismith et al., 1998), USA (Henschel, 1994) and Finland (Arvela, 2001).

Table 9.Comparing Effectiveness of Different Construction Solutions to Avoid Radon in New Houses

Systems	Methods	Effectiveness
Barrier Membrane		
Barrier membrane installed in 64 new houses during construction in Northamptonshire, UK (Groves-Kirkby et al., 2006) Compared the results with a study of post-construction remediation (Denman, Phillips & Tornberg, 2002).	Radon levels measured in the main bedroom and living areas for three month using track-etch detectors.	The mean annual radon level went below the action level (200 Bq/m^3) in 40% of the new houses. Whereas the post-construction remediation found over 75% of houses below the action level.
With or Without Barrier Membrane and additional Block and Beam Protection		
Construction solutions for three different group of houses were: a) protected floor with barrier membrane and walls with cavity tray and compared with b) unprotected floor (no membrane) and c) protected with additional block and beam floor (Scivyer, 2001)	Radon levels measured in a) 131 protected houses and compared with b) 245 unprotected ones' and c) another 89 protected with additional block and beam constructed from 1990 to 1994.	a) 96% protected houses found below the action level compared to b) 80% unprotected houses c) almost all houses protected with added block and beam floor remained below the action level. This supported previous UK study conducted by Woolliscroft et al (1994).
Radon piping installed under the floor slab of new houses		
Finland requires radon preventive measures as a condition of construction permit (Valmari et al., 2014).	Radon piping installed under the floor slab that can later be activated if radon level goes over action level (400 Bq/m^3)	Maximum 45% effectiveness noted in in new houses compared to 24% in old houses after activation of the radon piping.

3.2 Review Findings to Answer the Research Questions. The objective of this review was to answer three research questions. Firstly, the findings presented above shows that most experimental and intervention studies conducted in Europe, Australia and North America with the active sub-slab soil or sump-depressurization system (SSDS) reduced radon level-up to 99% in existing houses initially having higher than the reference levels. This method provides a consistent high radon reduction at a reasonable cost as compared to other passive methods (EPA, 1993). In areas where the installation of an SSDS is impractical, and a rapid radon reduction is needed, an alternate method, called sum-pump in the UK, is also proved 99% effective. Sump-pump is based on the same fundamental procedure for old houses such as dilution and pressure change and accomplished by an active pressure-modifying sump with an exhaust fan (Scivyer, 1993). Thus, it was found that overall SSDS (either soil or sump) is the most effective single radon remediation techniques for the existing houses. However, remediating existing houses with SSDS is always more expensive than installing a barrier method or radon-proof membrane during new house construction.

Studies of new construction indicate that achievement of the best reduction with a single method depends on careful consideration of specific characteristics of a house (Denman, Phillips, & Tornberg, 2002; Groves-Kirkby et al., 2006; Scivyer, 2001). The foremost technique for new houses is to place a radon-resistant membrane across the entire basement with caulking that prevents radon from entering along the walls at the forefront. In high radon areas, this is reinforced with sub-slab natural ventilation where the floor is suspended or with a passive sump below the level of concrete ground-floor. In either case, where the radon level is very high, a power-driven fan fitted to the sump can strengthen the system (Scivyer, 2001). However, radon mitigation in Alaska and colder areas in Canada proved to be more effective when sealing of basement with vapour-proof polyethylene membrane and caulking of sidewalls was combined with an SSDS (Seifert, 2009). Other radon mitigation techniques tested in the UK and other EU countries with variable levels of evidence for success are (i) ventilation: balanced heat recovery ventilation; active and passive indoor, and underfloor ventilation. (ii) house pressurization, (iii) simple sealing and (iv) radon-well.

Some Nordic countries like Sweden experimentally recorded 100% reduction of preceding radon level with Heat Recovery Ventilation (HRV) system, but it has been only 25-75% effective in general household use (Akbari & Oman, 2013). Nonetheless, it works only in airtight condition and suitable where an excessive winter condensation is to be averted. Likewise, Finland noted up to 80% effectiveness by employing the radon-well technique in both the existing and new buildings (Holmgren & Arvela, 2012). Where in larger buildings, an increase in ventilation rate proved to add efficacy. Such ventilation was achieved together with a heat exchanger to warm incoming air in the winter and to cool it in the summer. They usually construct radon well close to the building and use a fan to exhaust radon gas. The efficiency of the well depends on the homogeneity of soil layers, soil permeability, moisture content, depth of the well and ability of the pump used. The well functions better only in coarse types of soil and one radon-well influences a distance of 20–60 m (Holmgren & Arvela, 2012).

In some areas where the radon level is comparatively low, ventilation of crawl spaces and closed basement rooms is proved enough. Where weather allows, the simple opening of windows can bring about a temporary reduction in indoor radon, but this is unlikely to provide a permanent solution (Holmgren & Arvela, 2012; WHO, 2009). Similarly, a study conducted by the US EPA (1993) showed that natural ventilation could reduce radon concentrations by up to 90% when a sufficient number of windows and vents were open, a solution impractical in cold countries.

Among other mitigation approaches, filtration has a relatively long history in mitigating the inhalation exposure from radon decay products. A variety of methods such as electro-filter, an air cleaner with a mechanical filter (Kojima, Abe, & Fujitaka, 1992) and high-efficiency particulate air filter (HEPA filter; Kranrod et al., 2009; Rajala et al., 1985; Yasuoka et al., 2009) have been tested. However, no significant effect is noted so far. Thus, the U.S. Environmental Protection Agency (2009) does not recommend air filtration as a measure of radon mitigation.

Evidence gathered by the WHO (2016) showed that an active SSDS along with placing a plastic membrane in between the basement slab prevented radon exposure by up to 98%. Whereas only active SSDS could avert radon gas up to 90%, and passive mitigation reduced indoor radon levels up to 50%. Similarly, when used separately, both the barrier membranes and block and beam constructions decreased the levels of indoor radon by up to 50%. Whereas, employing these together substantially reduced indoor radon levels up to 75%. It is suggested that any mitigation system used should reduce radon levels by more than 50% (WHO, 2016). When using a passive system, it could be easily upgraded to an active mode once the radon level goes up. Also, the methods should be energy efficient, remove other soil gases, control moisture and eliminate mould in the basements. An SSDS together with radon-proof membrane shown to serve most of these purposes. Therefore, it was concluded that a combination of techniques is always more effective than any single mitigation system.

Second, people in the cold countries start closing their doors and windows and switching on the furnace from the month of October. This is the time radon gas begins to build up indoors. The review shows that most of the residential studies measured and mitigated houses from October onwards. Thus, considering the meteorological and seasonal rise and beginning of the indoor accumulation of radon gas, late fall (October-November) found to be the best time to test a house for radon (El-Zaher, 2011). On the other hand, the best time to test and install a mitigation system in a house while considering the economy of the cost is during new construction, and for the feasibility, it is the time when the house is up for sale (Letourneau et al., 1992). Because this is the time to endorse the regulations and as there is a flow of cash, it is easy to find an option to bear the cost either by including it in the mortgage or negotiating the cost of mitigation between buyer and seller (Warkentin & Curry, 2018).

3.4. Factors Affecting Mitigation. The prime factors worthy of consideration while planning for residential radon mitigation include building characteristics such as age (Naismith, 1998), geographic location (Hystad et al., 2014), geologic formation (building constructed on uranium-rich bedrock (Marley et al., 2001); initial indoor radon concentration (Gunby et al., 1993) and amount of radon resulting from the construction materials (Groves-Kirkby et al., 2008), insulation and presence of double-glazing (Birovljev, 2005), soil conditions, weather and climate (El-Zaher, 2011; Gunby et al., 1993; Schubert et al., 2018). Among other fundamental factors are the suitable building site, standard foundation design and building materials as recommended by the universal good building practices (International Residential Code, 2017). Schubert, Musolff, & Weiss (2018) examined indoor radon concentration on meteorological parameters excluding the influence of forced ventilation and radon exhalation from soil and building materials. They found out that the fluctuation of indoor versus outdoor air pressure were the key driver for a continuous indoor/outdoor air exchange and thus, for the variation of the indoor radon concentration. Such variation occurs both in diurnal and multi day patterns. The diurnal variation of the indoor radon concentration was predominantly triggered by the diurnally changing indoor temperature and the associated expansion/contraction of the indoor air volume. Adding to this thermal breathing were diurnally recurring periods of low pressure within the container triggered by an elevated wind speed that generally arises during early afternoons. This influence is founded on Bernoulli's principle. Besides its diurnally changing impact the latter effect resulted also in multi day breathing patterns associated to multi day periods of stronger winds. Thus, they concluded that while the thermal breathing is major cause of the diurnal variation of the indoor radon concentration, multi day radon variations are mainly the result of multi day wind speed patterns.

Indoor radon concentration reflects the balance between the rate of radon entry into a house from all sources and the amount of radon loss by natural radioactive decay and dilution through ventilating air (Wilson, Dundey, & Gammage, 1994). More precisely, the rate of radon entry into a building is the sum of contributions from soil-gas (generally the primary source), release from the building materials in some areas (Chen, Rahman, & Atiya, 2010). Water supply from well or borehole (Smith & Voutchkov, 2017), drinking water (Smith & Voutchkov, 2017) and combustion of natural gas used for heating and cooking (Mitchell, Griffin, & Casman, 2016). While radon entry into a room from building materials is essentially diffusive, entrance from the subsoil is pressure-driven (the effects of wind naturally generate a difference of few Pascal), indoor-outdoor temperature differences, and the use of heating, ventilation and air-conditioning systems (Schubert et al., 2018). On the other hand, radon loss depends on ventilation rate (units of air-exchange per hour) and to a lesser extent on natural radioactive decay (half-life of radon progeny ($\tau 1/2$=3.6 days). Continued changes in meteorological parameters and residents' lifestyle (windows opening, exhaust fans, AC and furnace using;) also influence these processes on a day to day basis (Font & Baxieras, 2003; Hystad et al., 2014; Janssen, 2003; Schubert, Musolff, & Weiss, 2018). Thus, the intervention effectiveness depends not only on the initial radon level and radon-prone areas but also on the individual household characteristics and residents' behaviours regarding the opening of door and windows; and passing the time outdoors. Among other factors are the cost of mitigation, willingness to pay for the energy consumption, accuracy of diagnostic measures, design and installation of the system in proper time and location (Brossard, Ottawa, Falcomer, & Whyte, 2015). Therefore, while the planner of radon remediation should be cognizant of these factors.

Among the recent developments, Collignan & Powaga (2017) used a numerical ventilation model in France and considered the effects of variations from depressurization and air change rate in the indoor environmental conditions on the radon entry rate and on the indoor radon activity concentration (IRnAC). In the context of developing an indoor energy consumption policy, the results showed that IRnAC was strongly correlated with the variations in the air permeability of the building associated with the ventilation regime.

4. Discussion

This review noted that many countries with high radon areas around the globe start recognizing the importance of healthy indoor atmosphere more rapidly in recent years than ever as evidenced by their adoption of new building codes in the legislation. This requires builders to install a passive radon impermeable membrane in between the basement slabs during all new constructions to prevent radon entry from the soil to residential buildings. However, the review of intervention studies revealed that merely placing a passive membrane is not the most effective practical solution; rather this should be reinforced by some active methods like a power-driven fan fitted to the sump (Scivyer, 2001). Where in extremely cold countries, this combination of passive membrane and caulking does not provide effective remediation, rather placing sub-slab perforated pipe (SSDS) systems that can be activated with fans when radon level goes high especially in North America proved to be useful (Seifert, 2009). In existing old houses of high radon areas, effective mitigation of indoor radon is achieved with the combination of house-specific long-term stable mitigation techniques such as an SSDS combined with the sealing of basement cracks and openings (Boardman & Glass, 2015; Maringer et al., 2001; Stanley et al., 2017). As we observed, in all situations, there exists a useful solution to fix the indoor radon and thereby to decrease the prevalence of radon-induced lung cancer risk. This is unique for human health risk mitigation from the exposure to radon gas compared to any other environmental hazards.

As noted the selection of an effective mitigation technique is contingent on a group of geologic, architectural, climatic, atmospheric, behavioural, and socioeconomic factors. In the first place, the geologic condition where the house is built is crucial (Marley et al., 2001). To evade this problem, builders can consult radon maps that clearly mark the areas with high radon level. It is also critical to identify the sources and routes of radon entry; it's building up and circulation; and how the building features relate to all these aspects. The mitigation systems reviewed have considered more or less these factors and attained a certain degree of effectiveness in reducing the level of indoor radon. However, no mitigation system could address all of these factors and reduce the entire amount of radon for a sustained period. Instead, a thoughtful blend of measures could only lessen the level down to the action level (varied from country to country from 100-800 Bq/m^3). This underscores the fact that there is a continuous discharge of radon gas from building materials, in case the flow from the soil is blocked entirely and permanently. Therefore, in no time one can be 100% risk-free. This indicates uncertainty of the risk and justifies ICRP's (2010) recommendation to mitigate indoor radon even at a lower level to keep the level as low as possible, not to eliminate as that is impractical (Vaillant & Bataille, 2012).

Studies showed that indoor radon is related to the age of the house (Barros-Dios, Ruano-Ravina, Gastelu-Iturri, & Figueiras, 2007). There have been innovative studies in recent years that included home metrics in radon assessment like the year of construction, type of building and foundation, floor and room sizes where radon level was measured (Stanley et al., 2017). They noted that new houses built after 1992 had radon levels, on average 31.5% higher than those in older homes (Stanley et al., 2017). Similarly, they found that homes with larger floor-plan size had greater slab shrinkage causing wider floor-to-foundation gaps; and higher vault ceiling had the greater potential thermal stack effect creating an enormous negative pressure at the basement level – these draw more radon gas indoor. Besides, they noticed higher radon levels in the basement and utility spaces due likely to reduced ventilation and proximity to radon entry points. Thus, they wondered that millennial home-engineering practices that seek energy efficiency with insulation could compromise air exchange and increase the mean indoor radon level (Stanley et al., 2017). These findings open up the avenue to explore more about the architectural, engineering and building metrics that interact with the environmental factors to generate evidence for designing more appropriate radon mitigation strategies.

While several factors are related to radon remediation, the focus was on the effectiveness regarding how much the system reduces radon below the action level. Although evaluating the cost-effectiveness was out of the scope of this review, a few cost-effectiveness studies came across the review. No study strictly followed any health economic model to evaluate the cost-effectiveness of a particular radon remediation technique. However, from the cost-effectiveness perspective, overall radon mitigation strategy is geared to target the most vulnerable houses in high radon-prone areas and to achieve mitigation during all new construction irrespective of radon-prone areas. Such strategies are considered more cost-effective and less disruptive than performing any mitigation after the house is complete. Studies with homeowners in high radon areas provided further insight into their intention to pay and noted that people intend to pay more for remediation when the risk was high and adequately explained (Spiegel & Krewski, 2002). This underscores the evidence-based information provision for the residents in high-radon areas. Commercially found that on an average installing a radon mitigation system in existing house costs about $ 3,000USD /€2634, but the cost of placing a radon-proof membrane within the basement floor with associated caulking of sidewalls during new construction always remains less than $ 1,000 USD/€ 878 (Home Advisor, 2018). A recent publication from CARST (2018) showed the cost range from $200 to $1,000 CAD with an average of $2,900. These facts from the market correspond with the review finding that remediation during construction is far better than doing it later.

Though the cost of mitigation may not be a significant financial burden for some, public support fund can certainly encourage low-income households to mitigate their houses for radon proactively. In the review, a break of silence was heard on this issue especially in many European countries (Norway, Denmark, Sweden, Switzerland, Finland and the UK) and some of the US states. Although seven Canadian provinces and all three territories have updated radon legislation, Canada does not use either spending or taxation powers to assist citizens with the cost of radon mitigation. However, most jurisdictions who adopted radon legislations (Canadian Environmental Law Association, 2017; National Conference of State Legislatures, 2015; Stationery Office, 20008; Valmari et al., 2014) suggested: a) disclosure of known radon hazards upon the sale of the property. b) Certification for mitigation contractors, c) surveying radon concentrations indoors. d) Issuing the license for radon industry. e) Inclusion of passive radon resistant construction. f) Provision of public education, testing, training, technical assistance, remediation grants, and loan or incentive programs and g) construction permit requires consideration of radon preventive measure. Consequently, homeowners became more active in testing but in cases over 53% of them are not mitigating their existing houses due mainly to financial cause, followed by other reasons like insufficient guidance (19 %), unavailability of radon professionals (12 %) and deeming unnecessary (9%; Valmari et al., 2014). Therefore, a reasonable next step for the federal government of Canada would be to expand the National Radon Program to provide financial assistance for the costs of radon mitigation to those in need of support. If done, this will send a powerful message that the problem is taken seriously, and a significant barrier is removed.

Finally, where perfect installation should ensure a significantly lower radon level in a home, in practice, error in installation or damages during construction or shrinkage of the basement with time can result in ineffective protection. This warrants training of radon mitigation personnel and builders as well as the need for post-remediation testing. The studies by both Long et al. (2013) and Valmari et al. (2014) showed that radon mitigation efficiency relates to the initial radon level. This underscores the importance of using different mitigation techniques based on the high (21% of homes exceeded the reference level) and low-risk areas (0.5% to 4% of houses above the reference level). This also supports the utility of a valid radon map developed on the ground in selecting the mitigation option. Most of the habitations in Canada are built over the Canadian Shield – the high-radon zones. Future construction of buildings can consider incorporation of the radon-prone regions in the land utilization maps to avoid the hazard from the outset.

Further research can investigate the differential contribution of identified factors on indoor radon level and their impacts on the effectiveness of different radon mitigation systems. A qualitative study can explore residents' preference for and satisfaction with the mitigation systems in terms of their functionality and maintenance. It is still unclear how long a mitigated indoor environment will be adequately protected. The wide variation in effectiveness indicates that some of the mitigation systems are failing for various reasons. It is also likely that the effectiveness and efficiency could be enhanced by improving the methods, regular inspection, re-testing and maintenance protocols (Long et al., 2015; Rahman & Tracy, 2009). It is yet to determine how often the radon levels in a mitigated house be re-measured - yearly, biannually or in a five-year interval? Thus, accredited training of radon professionals- architects, engineers as well as constructions workers and property managers. These are to be implemented at two different levels to achieve these objectives. Again, despite the technical success of mitigation systems, only a small fraction of buildings with excess radon are currently being mitigated. Resounding the remark made by Rahman & Tracey (2009), recent experimentations in the area forecast innovation of some inexpensive mitigation techniques very soon for them to be accepted widely by the residents of high radon areas.

5. Limitation

The effectiveness was considered in terms of a remediation technique's ability to reduce radon below the action level. As no article was found that conducted cost-effectiveness of any radon mitigation system following the health economic models, no economic evaluation of mitigation measures was considered. There is an abundance of experimental studies done in single model houses or intervention with a few houses; thus, generalizing the outcomes to the broader housing population was difficult. Besides, there were very few studies that exactly followed the specifications mentioned in the new building codes for the residential building adopted in Canada and elsewhere recently. Future review with studies on the implementation of new building codes would provide updated evidence. To avoid reporting bias, documents were searched from grey literature, looked into the reference lists of selected peer-reviewed articles and contacted authors for further data. While selecting articles, publication status was not considered; thus, conference papers, reports and even articles in the press were included. However, there remains the possibility of publication bias as selective findings were reported regarding the effectiveness of mitigation systems while some articles investigated other topics, not within the scope of this systematic review. A last moment search was made in December 2018 to find the latest evidence to corroborate findings presented in the discussion section. This is to ensure that there was no risk of incomplete retrieval of the relevant and latest research on the topic.

6. Conclusion

There exist effective solutions to reduce the human health risk from environmental exposure to indoor radon; thereby, to decrease the prevalence of radon-induced lung cancer. Some duly tested radon mitigation systems were identified that could effectively reduce radon in both new and existing houses. Thus, it was concluded that in existing homes, the active radon mitigation systems are more effective than the passive ones. The active sub-slab or sump depressurization system (SSDS) is the most effective of all remediation techniques reviewed. The active ventilation measures are the next most effective; passive ventilation was less successful. Contrary to the new building codes, placing a passive barrier membrane alone has found inadequate in the newly constructed houses. The review indicates that in high radon areas and for larger buildings, effective mitigation of indoor radon can be achieved with a combination of house-specific long-term stable mitigation techniques rather than using any single measure, particularly in the extreme cold countries.

The best time to test and install the mitigation system in a home is during late fall (October-November). Some of the identified factors worthy of consideration while planning for mitigating dwellings for radon are initial radon level, design of the building, geographic location, underlying bedrock, soil conditions, nearby water drainage or river system, weather and climate of the area. As there is not enough evidence about the long-term viability of any radon remediation technique, periodic radon measurement is recommended after remediation to ensure that concentrations continue to remain below the action level. For the practical implementation of radon mitigation in the future, training of the constructions professionals, information provision for residents, the establishment of public funds, incorporation of radon-prone areas in the land utilization maps, and enacting building codes deemed essential.

Appendix 29. Country wise collection of radon mitigation interventions

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Authors' contribution: First two authors searched literature independently, the first author synthesized data and prepared the manuscript, and the second author reviewed and revised all data and manuscripts several times. The third author technically guided, supervised and critically reviewed the final draft. All three authors agreed with the final version of the article and authorized for publication without any reservation.

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Note: The next chapter presents the mixed methods analysis of both quantitative and qualitative findings and a global discussion summarizing the results of all articles.

Chapter Eight: Mixed Methods Analysis and Global Discussion

Introduction

The mixed method applied in this project can be described as an exploratory sequential method. As already defined, mixed method research is an investigative design that is used to study a phenomenon in-depth by applying multiple rigorous and persuasive methods to collect, analyze and mix both quantitative and qualitative data in a single study (Creswell, 2014). The methods are used concurrently or in various sequential phases of research or in a series of studies to tell a complete story (Creswell & Plano-Clark, 2011).

Accordingly, we adopted an interdisciplinary population health approach and integrated concepts and theories from multiple disciplines such as philosophy, psychology, epidemiology, health promotion, and social science and public policy domains. Specifically, we adopted a pragmatic worldview, developed our investigative tools with the constructs of protection motivation and psychological theories of risk perception to look for empirical evidence.

Our population health approach was based on the assumption that interrelated conditions and determinants impact health outcomes throughout the life course, and there exists a systematic pattern through which the effects from exposure to a health risk occur and are perceived (Kindig & Stoddart, 2003). This approach is in accord with the pragmatic philosophical worldview that employs diverse and systematic ways to find how things happen, what works and what does not, by giving primacy to the importance of the research question and valuing both the objective and subjective knowledge (Creswell et al., 2011).

Evolution of Our Mixed Methods Study

The initial scoping literature review based on the ‘Integrated Population Health Risk Assessment and Management Framework’ (Krewski et al., 2007) had a broad focus, and it discussed how a set of interacting determinants affect residents’ exposure to indoor radon gas. The review also clarified some of the concepts and variables that could be considered in this study. Our empirical project started with a qualitative mini-pilot study and followed with a complex survey and ended with the main qualitative interviews. In the beginning, the study was sequential, as we developed a survey instrument with insights collected from the preliminary qualitative pilot study and continued with the survey. Based on the initial survey outcomes, an interview protocol was designed, and qualitative data collection started. However, during that time, more survey responses were coming in; thus, two methods overlapped and both the quantitative and qualitative data were collected concurrently in that stage of the study.

Initially in our study, qualitative and quantitative data were analyzed separately and presented in two articles. Then, a mixed method analysis was conducted to relate the findings from both studies and to enhance explanations of the primary outcomes. The purpose was to get the best out of each method through triangulation of findings that could furnish explanations for the unexpected or unusual findings. As we discussed earlier, research in health sciences has showed how the findings of the qualitative study might help to compare the baseline measures gathered from quantitative study or to explore the extent where such findings of a qualitative study could be generalized to another population or setting or to generate hypotheses or research questions for further research.

The mixed methods research questions. To look back, the two mixed methods research questions were: a) How do radon health risk perceptions vary among the residents' sub-groups with the differences in age, gender, education, income, race/ethnicity, and homeownership status?

b) What are the social antecedents determining differential radon health risk perception and motivation for preventive health actions?

Background of Mixed Methods Data Collection

As mentioned before, the quantitative survey instrument contained both structured and open-ended questions and was conducted in winter 2018. A concise analysis of quantitative data is presented under the quantitative research part that was done for the purpose of publication to meet the requirements of the targeted journal. Here, we present the outcomes of further analyses with the aim to corroborate, compare or contrast with the findings of the qualitative study.

As we were theoretically based on the Protection Motivation and Psychological Theory of Risk Perception in designing the investigative tools, we collected evidence that supports the constructs and dynamics of these theories. We also identified the associations among the measured variables that again varied across the population sub-groups according to their demographic and socioeconomic characteristics as already described with the quantitative findings and these are cross-examined with the qualitative results in the next sections.

Mixed Methods Analysis

Demographics of survey participants. Our quantitative sample comprised 557 residents from the Ottawa-Gatineau CMA (Table 10 below). As mentioned before, in this randomly selected sample, homeowners and tenants are represented in a ratio of 71: 29, exactly as they are in the population. The gender ratio could not be maintained as many preferred not to identify themselves. Age of our sample residents skewed to the older people (65 years and above) mostly for homeowners than tenants. Race-wise, visible minorities were highly, and Canadian Aboriginal people were under-represented. Most of our survey takers had some university education, and people of the lower middle-income group had taken the survey in a comparatively large number.

Table 10. Demographics of Survey Participants

Sociodemographic Variables	Overall Participation n (%)	Homeowners n (%)	Tenants n (%)
Characteristics	**557 (100%)**	394 (70.7%)	163 (29.3%)
Gender			
Male	291(52.2%)	193(49%)	98 (60.1%)
Female	224 (40.2%)	170 (43.1%)	54 (33.1%)
Not willing to identify	42 (7.5%)	31(7.9%)	11 (6.7%)
Age groups			
18-24 year	83 (14.9%)	51 (12.9%)	32(19.6%)
25-34 year	58 (10.4%)	42 (10.7%)	16 (9.8%)
35-44 year	59 (10.6%)	42 (10.7%)	17 (10.4%)
45-54 year	85 (15.3%)	63 (16%)	22(13.5%)
55-64 year	106 (19%)	69 (17.5%)	37 (22.7%)
65 and above	166 (29.8%)	127 (32.2%)	39 (23.9%)
Race/Ethnicity			
European Canadian	375 (67.3%)	271 (68.8%)	104 (63.8%)
Aboriginal Canadian	14 (2.5%)	12 (3.0%)	2 (1.2%)
Visible Minorities	120 (21.5%)	76 (19.3%)	44 (27.0%)
Prefer not to answer	48 (8.6%)	35 (8.9%	13 (8.0%)
Education			
Elementary	1 (.2%)	0 (0%)	1 (0.6%)
Some high school	6 (1.1)	5 (1.3%)	1 (0.6%)
Completed high school	60 (10.8%)	32 (8.1%	28 (17.2%)
Some Community/technical			2
college/CEGEP	60 (10.8%)	36 (9.1%)	4 (14.7%)
Completed Community/technical			
college/CEGEP	75 (13.5%)	55 (14%)	20 (12.3%)
Some university	48 (8.6%)	39 (9.9%)	9 (5.5%)
Undergrads	187 (33.6%)	137 (34.8%)	50 (30.7%)
Master, PhD	100 (18%)	74 (18.8%)	26 (16%)
Post doctorate	11 (2%)	8 (2%)	3 (1.8%)

No schooling **Prefer not to answer**	3(.5%) 6 (1.1%)	3 (.8%) 5 (1.3%	0 (0%) 1 (0.6%)
Income groups **<$40K** **$41K-$75K** **$76K - $100K $101K- $150K** **>$150K** **Prefer not to answer**	 60 (10.8%) 147 (26.4%) 94 (16.9%) 106 (19%) 68 (12.2%) 82 (14.7%)	 29 (7.4%) 101 (25.6%) 66 (16.8%) 86 (21.8%) 54 (13.8%) 58 (14.7%)	 31 (19%) 46 (28.2%) 28 (17.2%) 20 (12.3%) 14 (8.6%) 24 (14.7%)

Qualitative study participants. The sample of the qualitative study consisted of 35 interviewees purposefully selected from the above cohort (Table 11 below). As our purpose was to collect more information, we selected survey takers who showed some degree of radon knowledge and either tested or mitigated their houses for radon. For this reason, the sample was underrepresented by the tenants and people from the low-income group.

Table 11. Qualitative Interview Participants

SP	Age-group	Sex	Race	Education	Child	Occupation	Income	Home-ownership	TBMGF
SP1	45-54	Male	EC	College	1	Pub Service, fed. govt.	101-150K	H	Yes, Children (past)
SP2	25-34	Male	VM	UG	2	Pub Service, fed. govt.	41-75K	H	Yes, self
SP3	35-44	Male	VM	College	3	Pub Service, fed. govt.	41-75K	H	Yes, Children
SP4	18-24	Male	EC	College	0	Business	101-150K	H	No
SP5	35-44	Male	VM	UG	3	Business	76-100K	T	Yes, Children
SP6	55-64	Female	EC	Ph.D.	0	Professor, Virologist	>40K	H	No
SP7	55-64	Male	EC	UG	1	Sales Person	PNA	H	Yes, Children (past)
SP8	55-64	Male	VM	College	1	Job in Ptv. Company	101-150K	H	Yes, self
SP9	55-64	Male	EC	Master, Eng.	0	Redt. Engineer	76-100K	T	No
SP10	35-44	Female	VM	MBA	1	Project Manager	PNA	T	Yes, Children
SP11	45-54	Male	VM	Master, IT	3	Business	101-150K	H	Yes, Children
SP12	65+	Male	EC	College	0	Retd. Sales Manager	151K+	H	No
SP13	65+	Male	EC	UG	0	Retd. Foreign Service	101-150K	H	Yes, self
SP14	25-34	Female	EC	UG	2	Homemaker	>40K	T	Yes, self
SP15	45-54	Male	EC	UG	0	Retd. Sales Person	76-100K	H	No
SP16	65+	Male	EC	Master	1	Redt. Engineer	PNA	H	Yes, Children Grand often
SP17	55-64	Male	EC	UG	0	Retd. Businessman	>40K	T	Yes, self

SP18	65+	Male	EC	UG	0	Retd. RCMP	101-150K	H	Yes, self
SP19	45-54	Male	VM	UG	2	Eng. Electrical	76-100K	T	Yes, Self
SP20	65+	Female	EC	High School	0	Pub Service, fed govt.	76-100K	H	Yes, self
SP21	65+	Male	EC	High School	0	Retd. Ptv. Service	76-100K	H	Yes, self
SP22	65+	Male	EC	Ph.D.	0	Retd. Professor	41-75K	H	No
SP23	55-64	Female	EC	Master	0	Retd. Veteran	151K+	H	Yes, self
SP24	55-64	Male	EC	Master	0	Retd. Veteran Eng.	101-150K	H	Yes, self
SP25	65+	Female	EC	UG	0	Retd. Comm. Officer	76-100K	H	No
SP26	55-64	Male	EC	High School	0	Retd. Veteran	41-75K	H	No
SP27	65+	Male	EC	College	0	Retd. Naval Officer	101-150K	H	Yes, self
SP28	65+	Female	EC	UG	0	Data Analyst	41-75K	H	Yes, self
SP29	55-64	Male	EC	Master	0	Eng. Construction Consultant	151K+	H	Yes, self
SP30	55-64	Male	EC	Master	0	Retd. Manager	76-100K	H	Yes, self
SP31	65+	Female	VM	College	0	Pub Service, fed govt.	101-150K	H	No
SP32	55-64	Male	EC	College	0	Local Govt.	101-150K	H	No
SP33	65+	Male	EC	Master	0	Manager, Bell Canada	41-75K	H	No
SP34	35-44	Male	VM	College	2	IT Consultant	76-100K	H	No
SP35	65+	Male	VM	Ph.D.	0	Professor, Chemistry	101-150K	H	No

Legends: SP: Study Participants, EC: European Canadian, VM: Visible minorities; H: Homeowner, T: Tenant; TBMGF: Time spent in basement and ground floor. Child: Number of children lived or spent time in the basement. Italicized participants have mitigated their houses for radon.

Source of Radon Information

From the quantitative study (Figure 14 below), we knew that the majority of residents (54%) learned something about radon from the mass media including television, newspaper and magazine etc.

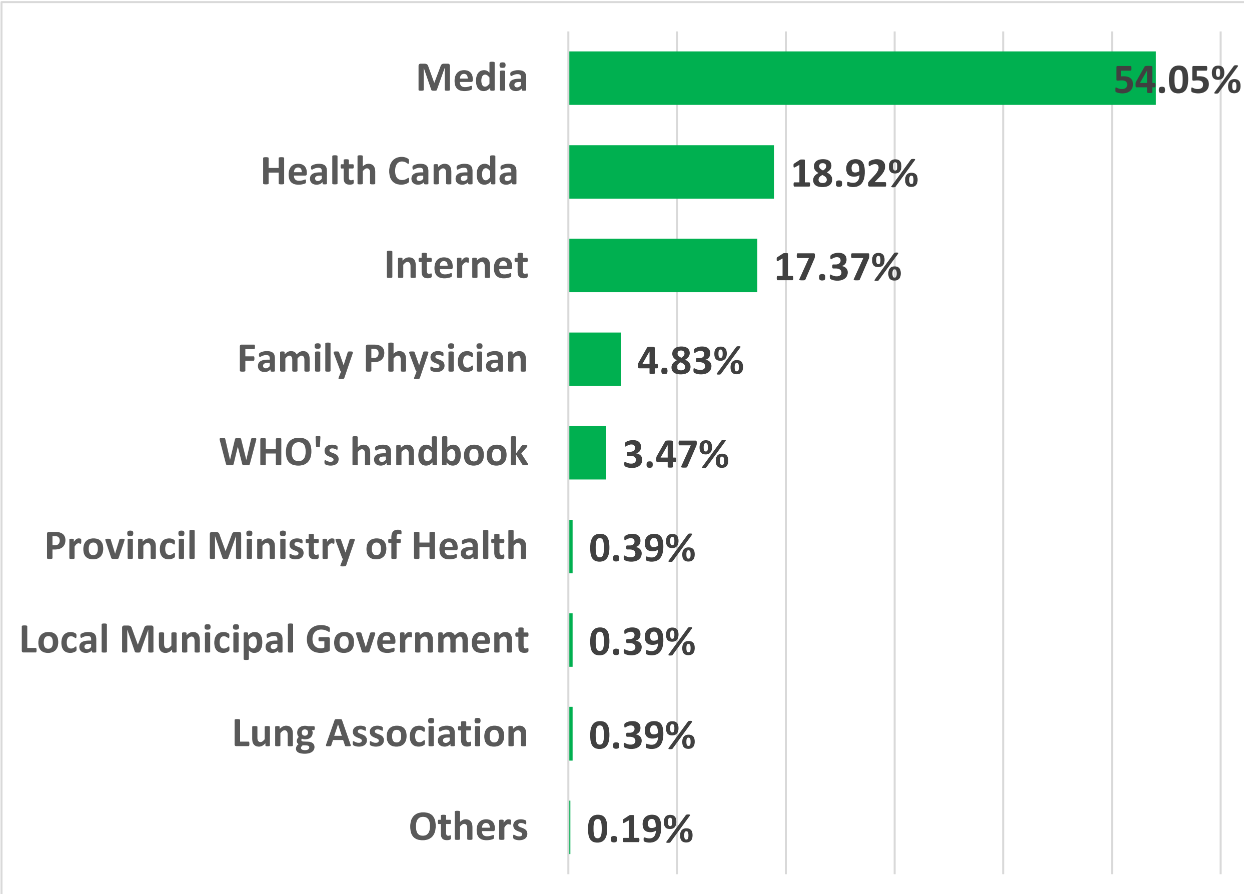

Figure 14. Source of Radon Information from the Survey Question

Whereas the qualitative findings provided us with the breakdown of this information. Where we found that most residents (28%) learned about radon for the first time from local newspapers or magazines, not from the popular mass media - television that usually comes to mind in the first place.

“There was a report in the Ottawa Residents, a local newspaper in the Kanata area that talked about radon gas.” (SP19).

““I read something about it years ago, in the Maclean’s magazine” (SP18).

Surprisingly, a large number of residents (20%) got to know about radon for the first time in their lives from the current (this) study.

"You delivered a presentation in the community center, and I heard from that" (SP3).

"I had not heard of radon till I was contacted to participate in your survey" (SP10).

"I never heard before you contacted me and sent me the link. I read everything you sent me" (SP14).

"The first thing I heard about radon was your ad; from the links that you sent to me" (SP28).

"I heard about it from your study" (SP25).

Others heard from their friends and peers, only 8% from came to know from the internet, 5% heard on the radio, and 3% from other sources (Scientific article, NRC etc.). Although these percentages do not necessarily represent the views of all Canadians, a comparative idea can be drawn about the access and impact of the mass media on our defined population. It was noted only in one instance from the interviews where watching a story of a non-smoking woman on television motivated a resident to test for radon and mitigate the house. This was a case of lung cancer where a doctor was shown to indicate the possibility of exposure to radon for the diagnosis of lung cancer of that woman.

"I was watching a medical program on TV that was doing a feature about a women and cancer, specifically lung cancer. The women in the program who got lung cancer did not smoke. They had a healthy lifestyle, they were fit, they exercised, but they still got lung cancer. So, the doctor was trying to find out –how was that possible? The cancer researcher, I don't recall his name, said that there is a high possibility that it was radon gas… So, they recommended to stay healthy, to take action, and directed to have your house tested to see if you are at risk of radon gas or cancer" (SP7).

Although this instance demonstrates the substantial impact of television; thus, it underscores the importance of such live campaigns. However, it also shows the lack of reach of such programs to the greater population. The same was manifested from the response to an open-ended question in the survey. When asked, what else you know about radon (Q.29; Figure 15 below), most survey participants (52%) responded 'nothing' as shown in the word cloud below.

Variations in radon health risk perception. From the survey, we found that the majority of residents did not know much about radon whereas the qualitative study provided evidence that although most of them knew very little, some residents possessed in-depth knowledge about the health issue. We were able to explore the reasons that lie behind the different level of knowledge and perception across population sub-groups.

Figure 15. Word Cloud of Responses to Question 29 in the Survey

These included a) *personal* health consciousness, especially, if someone was a lung cancer survivor; b) *familial* – being concerned about the health of children living in the basement; c) *social* – interaction with friends and witnessing others in the community who were diagnosed with or were suffering from lung cancer, or visiting a home fair; d) *occupational* – such as hearing about the risk from a colleague, taking part in training at one's workplace or learning as a part of one's job. The in-vivo quotes from the qualitative interviews support these variations:

Personal

"I am health conscious; if I know something is a risk factor, I would go for fixing that. I learned that all homes have a certain level of radon" (SP7).

"Well, I am a cancer patient; I am in remission. I have already problems with my lungs, so, I could not afford any more insult (exposure to radon) to my lungs. When I found the radon reading, even though it was not super high, I am not going to sit there and do nothing" (SP24).

Familial

"My daughter does sleep there (basement) quite often. So, I am concerned about her sleeping in the basement and a buildup of radon" (SP23).

"So, in our case, our son was living in the basement, it was constantly closed up, we never opened the doors, never opened the windows" (SP1).

Social

"We had friends who live a few kilometres from here, who told us about radon. This increased our awareness" (SP1).

"There is a man of 60 in my neighbourhood who got lung cancer. I am thinking what the cause may be - smoking, radon or any other cause might be. This makes me think about radon" (SP30).

Occupational

"I was trained in hazardous materials operations, as part of the fire department but more for the knowledge but not exactly to be active but to understand what the risk may be and thus, I came across also to radon gas" (SP32).

"I was a salesperson, sales of technology, all different types of technology, … (I did) market or consumer analysis… there were medical clients; they were dealing with radiation, that's where I know about radon- from the kind of equipment, testing kits" (SP12).

Therefore, our qualitative study enhanced understanding of the information gathered from the survey, otherwise our understanding would remain limited.

Table 12. Relations of Demographic Variables with the Protection Behaviours

Sociodemographic Variables	**Intention to test Wald (Sig)**		**Actual testing Wald (Sig)**		**Mitigation Wald (Sig)**	
Characteristics	Homeowners	Tenants	Homeowners	Tenants	Homeowner	Tenants
Gender	23.18(.00)	5.11(.02)	1.45(.22)	.44(.95)	1.4 (.23)	NS*
Age groups	38.36 (.00)	7.47(.00)	11.41(.00)	.64(.42)	8.7 (.00)	NS
Race/Ethnicity	1.3(.25)	.18(.66)	1.59(.20)	.18(.66)	.00(.95)	NS
Education	5.8(.01)	.65(.41)	.18(.67)	.00(.96)	.17(.67)	NS
Income groups	.37(.54)	.025(.87)	.20(.88)	.01(.91)	.06(.80)	NS
Length of year living in current home	.053(.81)	1.2 (.26)	3.3(.06)	2.3(.12)	.03(.85)	NS
Living space in the basement	4.5(.03)	.68(.40)	.34(.55)	.17(.67)	1.8 (.17)	NS
Consider radon a threat to your or family's health	5.7(.01)	.76(.01)	.05(.94)	1.78(.18)	.07(.78)	NS
Anyone from HH diagnosed with lung cancer	5.3 (.02)	.37(.54)	.34(.56)	.08(.76)	.02(.88)	NS
Worldviews	1.2(.26)	3.1(.07)	2.13(.14)	.94(.33)	.62(.43)	NS

Multiple Logistic regression: Method = Forward Stepwise. *NS: No statistics

Variation in Risk Perception

There was apparent variation across sociodemographic characteristics and how they differ between homeowners' and tenants' intention to test and actual testing and mitigation. Further to the quantitative analyses conducted earlier, we disaggregated the data between homeowners and tenants to explore variation of perception across sociodemographic factors. Table 12 above showed that gender significantly correlated with the intention to test for radon both for homeowners and tenants but not with actual testing and mitigation. This is a clue to the previous findings that women perceive a risk more seriously, but men are proactive in taking action (Slovic et al., 2004) but this was not clear from these statistics but manifested through the qualitative findings.

Age was associated with the intention to test for radon both for homeowners and tenants; when it came to actually test and mitigate homes, it was significant for the homeowners but not for the tenants. The reason also remained obscure until we got to know from the qualitative data that homeowners were comparatively older, had children and they cared for their health. We found no correlations of race or ethnicity with either intention to test or protection behaviours, neither for homeowners nor for tenants.

Education was significantly correlated with the intention to test for radon in the case of homeowners but not tenants. When we explored the qualitative data, we found that elder homeowners invested more times to study the health issue. On the other hand, among tenants who were not highly educated, could know about the risk from their workplace and colleagues. Similarly, income group was correlated neither with the intention to test or protection behaviours in both homeowners and tenants. This finding contradicted the qualitative result as residents who tested and mitigated homes for radon were generally well to do.

Likewise, the length of living in the current home was not correlated with either intention to test or protection behaviours, neither for homeowners nor for tenants. Instead, we found this to act as the basis of maladaptive behaviour, as stated by one participant: “I’ve lived in my house for forty years, but I don’t yet know, and everybody is healthy” [SP26].

“No, I don’t think (radon can be a threat to me and my family’s health) right now because I live in a new home” (SP2).

Our quantitative analysis showed that tenants spent more time than homeowners in the basement (32% versus 27%) consistently with their type of dwelling. However, this variable had a significant correlation with the intention to test for radon by the homeowners but not for tenants. This result practically complements our qualitative findings as most of the tenants in our small qualitative sample were living either on the ground floor or in the basement and obviously spending substantial time there.

However, when it came to test homes for radon, homeowners remained ahead of the tenants for reasons of authority or property ownership, financial ability and having children living in the basement, as we hinted above, and it would be clear from the analysis described in the next section.

Variations of Adopting Preventive Behaviours

We already reported on the outcomes of binary and ordinal regression analyses in our quantitative article. Here, we split the data file for homeowners and tenants that produced some different results (Table 13 below). Whereas all the perception variables were found predicting both the intention to test for radon as well as adopting protective behaviours by both homeowners and tenants, this differential analysis demonstrated varied results.

Table 13. Differential Outcomes of Binary and Ordinal Regression Modeling

Outcome Variables	Intention to test				Tested home for radon				Mitigated home for radon			
	Homeowners		Tenants		Homeowners		Tenants		Homeowners		Tenants	
Perception Variables	Wald/ Std. β	P	Wald/ Std. β	P	Wald/ Std. β	P	Wald/ Std. β	P	Wald/ Std. β	P	Wald/ Std. β	P
Perceived susceptibility of radon risk*	3.81	.04§	1.69	.02§	15.39	.00§	2762.3	.96	1.79	.77	NS	NS
Perceived severity of radon risk†	3.14	.03§	1.45	.00§	15.25	.00§	15.5	.86	2.72	.43	NS	NS
Synergistic risk perception‡	51.39	.00§	91.82	.00§	3.54	.06	67.9	.99	.02	.87	NS	NS
Smoke in home‡	22.19	.00§	10.83	.00§	3.89	.04§	81.7	.22	1.57	.21	NS	NS
Care for children‡	10.12	.00§	14.59	.00§	98.9	.00§	98.9	.04	2.52	.01	NS	NS
Social influence	9.62	.00§	4.54	.03§	103.0 9	.00§	3207.74	.00§	3.70	.05	NS	NS

*Ordinal regression model fit statistics, Likelihood for homeowner= 60.31, p < 0.00; 1, tenants=30.26, p<.00; and X2 for homeowners=71.59, tenants=42.79; df=7.

†Binary regression model, Cox & Snell R2 for homeowners=.224, tenants-.139; Nagelkerke R2 for homeowners=.300, tenants= .199; p<0.00, df=1.

§Values refer to the predictors that are significant in the model. SE=standard error of β; Std. β=standardized beta, χ2= Chi-Square statistic, df=degree of freedom. NS: No Statistics

While perceived susceptibility, severity and synergistic risk; smoking in the home, care for children and social influence significantly predicted residents' intention to test for radon for

both homeowners and tenants. All these variables predicted actual testing for homeowners, but only two variables (care for children and social influence) predicted testing behaviour for tenants.

Finally, the testing behaviour was converted to mitigating house only for homeowners' who had either a child living in the basement or had some significant social influence. In this case, none of the variables (children living in the basement and social influence) could motivate tenants to mitigate their house for radon. This varied finding can be explained either by their lack of authority over the property to make any structural changes or may be the limitation of financial capability. The qualitative data supported these findings.

Another explanation of this finding is that irrespective of homeownership, when both parties having children lived in the basement or on the ground floor was significantly correlated with their intention to test for radon and actual testing behaviour. This signifies their universal care for children that is the emotional or affective aspect of risk awareness as explained by the psychological theory of risk perception (Slovic et al., 2004).

Similarly, the finding of strong association between social influence and preventive behaviour matches with the qualitative finding. We identified particular instances of social influences where one witnessed a 60-year-old neighbour die of lung cancer who was not a smoker. Other participants mentioned hearing about the gravity of the risk from friends, peers and colleagues that motivated them to test their houses for radon.

Variations in Worldviews

Throughout the interviews, we noticed that residents' worldviews differed across population sub-groups. We were able to identify all types of worldviews as discussed earlier in reference to risk perception theories (Table 14 below).

Egalitarian or Societal or Communitarian worldviews. When asked about their worldview about radon in the survey, 28% of residents hold a communitarian or egalitarian view saying that radon is an overall problem from the coast to coast; so, property owners and tenants should get financial support to mitigate their homes.

When we delved into the qualitative data, we found that holders of societal, communitarian or egalitarian worldview were from the lower income groups with low levels of education, and most of them were tenants.

"If you are living in a condition where you are not aware of this risk; then, the government has the responsibility to inform them. In this case, this is a societal problem" (SP9).

Table 14. Different Worldviews in Residents of Ottawa-Gatineau

Worldviews	Frequencies
It is an overall problem from coast to coast; property owners and tenants should get support from the government to fix it. (Egalitarian)	28%
Radon affects individual persons, so they (homeowners or tenants) are responsible for fixing it. (Individualist)	26%
Radon is a natural hazard; government cannot be blamed for it. It's a shared responsibility of homeowners as well as of government. (Shared)	25%
It is a population health problem, governments and/or responsible agencies are responsible for fixing it. (Hierarchic)	21%

"I think it is a societal problem because three thousand people are dying of cancer that is caused by radon gas. It is a significant number of people especially when the most of it is preventable if they do the test and mitigate radon in their houses. Also, it is societal in the sense that building codes could be amended to reflect the will of the government better to prevent radon in the newly built houses in the first place" (SP14).

Individualist worldview. Another group of over 26% of residents said that radon affects individual persons, so the homeowners are responsible for fixing it. Similar individualistic views represented by the qualitative data are:

"I think it is more an individual problem than a government problem" (SP1).

"I do not see this is a societal problem. I think it is something that homeowners should take ownership of. The society can raise awareness of the issue and then, it is up to the individuals to the step to assess what their actual exposure level is. Then, take whatever steps need to be taken after the test - whether to mitigate or not" (SP16).

We identified the holders of such individualist worldview in our qualitative data to be generally highly educated and from the higher socioeconomic groups having adequate means to test and remediate their houses for radon. Thus, the finding from quantitative and qualitative data validated each other.

Shared Worldview. Another 25% of residents said that as a natural hazard, the government could not be blamed for it. It's a shared responsibility of homeowners as well as the government to fix it. This viewpoint was further clarified with the qualitative interviews as residents said:

"I think you cannot put the responsibility on one group. To me, it should be shared. The government has to do its job, and as members of the society, people have to do their job" (SP8).

"The initiative should be taken by the homeowners when their capacities exceed (financially), the government should be in support. It is for both, a shared responsibility. Both parties have something to do. It would be good if the government takes a larger share, but homeowners must take some responsibility" (SP12).

"It is shared in that homeowners take the share of testing the homes and then, if it is deemed to be at risk, then, sharing the cost with the government. That's what I mean by shared responsibility" (SP25).

Hierarchic worldview. Another 21% of respondents said that they are concerned about the health of the population; therefore, the government or responsible authority should be accountable for taking action. Such notion of natural hazard and hierarchic view of assigning the responsibility to the competent authority as a whole was evident among the interviewees who belong to lower-middle to low-income groups and most of them were tenants with a lower level of awareness.

"I think Health Canada has a big responsibility. Other than this, provincial government has the responsibility for health, and we learned recently that local government has to do something about it" (SP5)

"I think it was local government or Health Canada, a department of the federal government" (SP17).

Technological enthusiasm. In our qualitative data, a few residents also showed advanced technological awareness, they bought the latest real-time radon measurement device, installed the combination of radon-proof membrane and sub-slab depressurization systems in their renovated house; and are monitoring the radon level daily. The quote below supports such worldview:

"Yes, I have a real-time radon testing device. I took two photographs of the readings this morning. This shows 65, short-term average 31 and the long-term average is 68. The cut-off level is 200; so, we are definitely at the safe zone" (SP16).

Although we did not find any quantitative association of worldviews with either the intention to test or adopting prevention behaviours, the qualitative analyses helped to identify how social antecedents determine various types and levels of perception related to radon health risk in our target residents. The qualitative data also helped to explain how different worldviews were based on educational, occupational and socioeconomic backgrounds that impacted the intention to test for radon and to adopt preventive behaviours differently. Thus, we concluded that residents' radon health risk perceptions varied significantly with their social antecedents such as demographic contexts- gender, age, education; as well as socioeconomic conditions - homeownership and income levels.

Compliance with the PMT

From our quantitative data, we found differences in the level of perceived susceptibility and severity across the demographic characteristics of study participants such as age; as already noted older adults were more concerned than youths because of the reasons mentioned above. Female were found to have more concerns than men, but men stayed ahead in taking action. Institutional, occupational or professional knowledge, as well as self-education, could be attributed to a high level of concern and health awareness irrespective of the level of income. However, we could not find any differences in terms of race or ethnicity.

Homeowners were evidently more concerned and were ahead of tenants in taking adaptive actions. This is not only due to their financial capabilities but also due to being educated in different ways, becoming conscious for their own and their family's health. Our qualitative findings complement the quantitative ones in terms of showing differences in the level of perception of the susceptibility and severity of the risk.

We found statistically significant associations of residents' perception of the risk with their intention to test, actual testing and mitigating behaviours. The qualitative findings also showed the same response efficacy as those who thought radon as a real threat to themselves and their family members – carried out recommendations for testing and mitigation with the expectation of eliminating the risk. Again, in terms of self-efficacy, those who had the knowledge and financial ability executed the recommended courses of action successfully (Witte, 1992). Thereby, we found evidence of the constructs of PMT theory that the more residents believed they were susceptible to a serious threat, the more they engaged in the threat and coping appraisal. These comprehensions, in turn, determined the intention and ultimately the behaviour of a person that is termed protection motivation (Boer & Seydel, 1996; Figure 7). Thus, the PMT was implicitly followed as these two perception processes led a small group of residents to adopt an active adaptive response, but another large group to deny the threat. The latter group either took no action or followed a maladaptive coping mechanism in response to the radon health risk (Rogers, 1983). The signs of maladaptive coping responses were evident from the qualitative part of our study. Some examples are presented next.

Maladaptive behaviours. We defined maladaptive behaviours as taking actions departed from the recommended standard. We discerned some ideas residents held to be scientifically unfounded. As evident from the interview transcripts, some installed alternate systems (ventilation) that have less to do with radon mitigation, but they thought they were safe. [We cannot provide here an in-vivo quotation as this particular study participant did not permit us to quote].

Others felt that they are safe because they live in a new house "I live in a new house, and I don't think there is any risk" (SP2). This is also against the latest scientific evidence that confirms all houses have some amount of radon and new houses have it comparatively more than the older ones (Stanley et al., 2017). Although theoretically this is termed as maladaptive behaviour, for having a lower radon level, the study participants considered themselves under no serious threat of exposure from radon. There is also a problem with the Canadian guideline that sets the cut-off level at 200 Bq/m^3. This prevents public health professionals from advising residents to mitigate their houses while the test result is below this level. Some participants even took ignorance as a bliss: "I think, some people might be afraid of the fact that if there is radon and then, they have to spend money that they don't want. The old saying 'ignorance is bliss' yeah, I don't have a problem because I don't see there is one" (SP32). This is also a form of maladaptive response.

Such maladaptive responses, in reality, are placing some residents at additional risk. This includes behaviours that lead to inaction such as not taking any remedial action. Some people continued with smoking. This eventually results in the adverse health outcomes and thus, overlooking the opportunity to prevent lung cancer. Therefore, our study dealt with all four dynamics of the PMT: a) Perceived probability of the occurrence or vulnerability or susceptibility to getting lung cancer. b) Perceived severity of a threatening event of having lung cancer. c) Response efficacy of the recommended preventive behaviour (perceived efficiency of the test and believing that the mitigation measures will eliminate the threat); and d) Self-efficacy (personally showing the ability to test and successfully mitigate their houses for radon). Thus, we noticed protection motivation was the result of an informed threat appraisal and coping appraisal, and as a mediating variable, these prompted, guided and in some cases, helped to demonstrate the protective health behaviours (Boer & Seydel, 1996; Figure 7 or Figure 10). Again, the qualitative findings showed correlations between residents' worldviews and adaptive actions taken in terms of testing and mitigation; thus, results obtained from the analyses of both methods validated the constructs described above in the Protection Motivation Theory and Psychological theory of risk perception.

Global Discussion

We have noticed from both the quantitative and qualitative investigations, the critical tool to raise public awareness, i.e. the mass media has not been adequately and effectively used to disseminate radon health risk communication message to the target residents. It was found to be so in the Environment and Household Survey of 2015 for the members of the public in Canada (Statistics Canada, 2016). This finding also corresponds with the previous historical analysis of the media coverage of radioactive gas in Canada (Nicol, Ryan, & Okocha, 2014). We were surprised to notice that many residents became aware of radon health risk for the first time from our survey (Khan, Krewski, Gomes & Deonandan, 2018). Thus, we had to make the same conclusions as was made nearly two decades ago that Canadian National Radon Program has not been highly effective in informing residents and in prompting action to reduce radon exposure (Spiegel & Krewski, 2002).

Although a few residents showed in-depth knowledge about the health risk, most others who came across radon information demonstrated misconceptions about the risk. This includes unrealistic optimism, low appreciation of the susceptibility and severity of the risk as were noted with past studies in the US (Weinstein, Klotz, & Sandman, 1988) and Ireland (Clifford, Hevey, & Menzies, 2012) among residents of high radon areas as some of them exactly believed that radon is a threat to others, and they have no likelihood of getting any lung cancer. Thus, our study demonstrated evidence of avoidance of risk message (Donohew, Lorch, & Palmgreen, 1991) or denial of susceptibility (Kunda, 1987) as was noted by previous studies. We also noted evidence that people were motivated and took action when driven by the emotional aspects of perception in addition to that of cognitive awareness (Khan et al., 2018). This finding corresponds with those of previous studies (Tversky & Kahneman, 1981; Slovic, Finucane, Peters, & MacGregor, 2004). Therefore, a simple transmission of risk information will have very little effect; instead, we should take strategic approach adding innovations along with the evidence gathered.

We also noticed that misconception of the risk is dissipated through either experiencing the harm by oneself or directly observing others to suffer as was evident from a resident who had a 60-year old neighbour or watching on a television show that a women – where both were otherwise healthy and non-smokers but had contracted lung cancer. Availability of such instances of harm motivates people to be convinced about the health risk (Hevey, 2017). However, conversion of such conviction to a health protective behaviour has not been straightforward. Psychological studies in this area showed that translation of risk information and transforming that into a health behaviour have to follow a series of complex stages and have to be influenced by various triggering factors both at the micro (personal, familial) and macro (social, occupational, economic, political) levels (Hevey, 2017; Weinstein, 1988; Weinstein, Sandman & Robert, 1991).

Therefore, for radon intervention to have a measurable impact, these factors need to be addressed. At the micro-level, people develop mini-theories that can make them defensive while confronting intimidating risk information (Liberman & Chaiken, 1992). Studies have showed that when a health message is personally threatening, people usually moderate their perception of severity about health risk, raise questions about the accuracy of the risk information, and process it in a subjective manner (Witte, 1992; De Wit, Das, & Vet, 2008). So, instead of merely delivering frightening risk message how much evidence-based that might be, we observed positive effect only instances when presenting the real-life scenarios such as live presentation on television of a non-smoking woman who contracted lung cancer with the presence of a physician who vividly expressed the possible cause of exposure to radon.

Such communication helps people to link the scenario to both their personal (e.g. diagnosis of lung cancer) and family members' (especially children's) health and acts as an incentive to engage in protective behaviours such as testing for radon. Since such mini-theories people construct vary in types, risk communication techniques must adopt innovative approaches such as using diverse media, varied forms of messages with an appeal to both the cognitive and emotional aspects of risk perceptions and engaging authentic agencies, professionals and celebrities in delivering the message. Evidence from the UK showed better outcomes when radon health risk communication campaigns were made repeatedly (Poortinga, Bronstering, & Lannon, 2011) and engaged authentic agencies (Poortinga, Cox, & Pidgeon, 2008) in high radon areas.

As already described, risk perception is a predominantly a subjective experience and risk management has to with the community norms. It has macro-level factors such as how the risk is viewed and who is considered responsible for managing the risk (Wang, Ju, Stark, & Teresi, 2000) – these structural barriers cannot be overcome only through risk communication messages. As we can observe growing community action against drugs in Canada and gun control in the US developed over consensus, such established social norms, consensus and action groups for radon would help motivate more people to adopt protective actions, especially in high radon areas. Fortunately, we found residents who were much enthusiastic about going out and convening others to assemble and engage in collective social action on radon. Others suggested the engagement of various public and non-governmental agencies as well as celebrities.

From our qualitative interview, we found that the cost of radon mitigation deters many residents from even testing their homes as the result might reveal an expensive problem to address a distant and ambiguous risk. Therefore, Canadian Environmental Law Association (2017) and others have long held that the logical next step for the National Radon Program would be to financially support residents, at least in high radon areas, to pay for mitigation. This could be either as a tax credit or grant.

Again, within the macro-systems level, actions through the health care system can play a vital role. Health care system in Canada is publicly-funded, and all levels of government (federal, provincial and municipal) have enacted wide-ranging regulations related to the mitigation of various health risks. Reflecting the residents' views that government is responsible for tackling the radon health risks, all levels of government can expand their responsibility regarding the provision of information, financial incentives, formulating policy and enacting effective laws and regulations to mitigate radon health risk.

While conducting interviews, I came to know that people of lower income groups, tenants renting house and people who live in rural and suburban areas - have a comparatively lower level of awareness, and they have less access to radon health risk information and resources than the property owners and those living in the cities. These observations were also noted previously by researchers in the field (Nicol et al., 2015). To this end, public health inspectors and environmental health professionals should support them with the necessary information and resources. People renting houses have no right to test or fix the houses for radon, nor can they oblige the property owners to do these by any law (Health Canada, 2014). Public health inspectors should encourage tenants to undertake preventive actions through some easy to adopt lifestyle practices to reduce exposure to radon. As mentioned at the initial scoping review (Table 1) such practices include talking about the risk, exchanging radon test kits as a gift, and moving children's sleeping place and basement offices to the upper floors. Likewise, one should keep doors and windows open for a few minutes whenever the weather allows. Tenants should talk to the landlord for testing and ask to see radon test results before renting a house and registering a child in a daycare centre or school. These would be effective only if there are mandatory provisions made by law as already passed in some provinces like Alberta and New Brunswick. Besides, one should avoid wood furnace, place a high-efficiency filter on the furnace, run a fan at a strategic location, opening the foundation vent, seal the cracks in the basement, place a plastic sheet over the exposed basement soil etc., are all beneficial (Larsson, 2014). Further, tenants can be encouraged to make formal complaints or request relief under provincial and territorial Rental Tenancy Acts. The Canadian Environmental Law Association (2017) recommends that tenants contact local public health staff if landlords are reluctant to take action on radon. In such cases, public health staff can help tenants if only radon mitigation is mandated by law.

As mentioned earlier, for setting the action level of radon at 200 Bq/m^3, people do not feel it necessary to remediate their houses when radon reading is found below this level. Thus, public health professionals have to educate people by translating scientific evidence. Research has shown that in Ontario, we can prevent more than twice the lung cancer mortality by setting the action level low to the World Health Organization's guideline level of 100 Bq/m^3. The impact would be four times higher if the level is put down to 50 Bq/m^3 (Peterson, Aker, Kim, Li, Brand, & Copes, 2013). Experts in the field have commented that this is feasible across Canadian provinces where geographic distributions of radon are comparable. Studies found that installing the radon reduction techniques are straightforward and they are able to reduce radon level effectively; and this will prove cost-effective in the long run through reducing the lung cancer loads (Nicol et al., 2015). Another critical role these professionals can play is to work with the local authorities of Canadian Aboriginal communities and encourage testing and remediation, especially in high radon regions. In rural and remote areas, usually people live in single-family homes rather than apartment or condominium buildings, so these areas have more ground-level dwellings than in urban areas (Nicol et al., 2015).

We came to know about a home inspector who alerted one (SP34) of our interviewees about the radon health risk while inspecting the house during a real estate transaction. We assume that home inspectors can be an active stakeholder to engage in raising awareness and escalating discussions about testing during all such transactions. The role of home inspector in raising radon awareness and testing had already been acknowledged by the researchers in the field (Nicol et al., 2015). Public Health Inspectors can also promote access to the Canadian National Radon Protection Program's online portal (2019) where residents can get the contact information about certified radon professionals for radon testing and remediation. It is noticed that specific population sub-groups who rent basements, reside or work in the ground and basement-level facilities, children who spend most of their day time in such daycare centres, people who live in long-term care homes or correctional facilities or social housing are particularly vulnerable and more at risk of exposure to radon than others. Evidence showed that the highest concentrations of radon are generally found in the lowest levels of a building; thus, these population sub-groups should be paid special attention. Public health inspectors should visit and discuss radon health issue with the managers, operators of ground- and basement-level facilities. They should also talk to the residents and provide information about the health risk (Nicol et al., 2015).

Our residents also suggested legislating real estate transactions and including a mandatory provision for property sellers to declare the radon status during all real estate transactions. Although not yet come into effect, CARST has devised a "*Radon and Real Estate Tool Kit*" explaining the advantages and disadvantages of different options for seller and buyer who should bear these responsibilities (Warkentin & Curry, 2018). In case the seller tests and mitigates, they assume that unconcerned buyers may not reimburse them for the costs. On the other hand, if the buyers test and mitigate they may have to absorb the cost. They proposed that there should be a binding procedure made by law that the banks recognize the problem and allow financing for a "mortgage plus improvements". In the absence of such formal law, they proposed an alternate option. It is a “Radon Indicator/Assessment” process that includes an initial radon assessment (4-day test) and provision of money into a special account if the result reach a certain level (CARST suggests 75 Bq/m^3 as a cut-off level during the heating season and 50 Bq/m^3 during summer or non-heating season). It will be followed up with a long-term test conducted during the upcoming winter after new homeowner moves in. The result will determine whether to use the money for mitigation or return it to the seller (Warkentin & Curry, 2018).

Such a radon contingency clause is used in other countries like in in the USA (specifically in Virginia and Michigan), seller and buyer come to an agreement to take remedial action or potentially lose the sale if later test found the radon level exceeding the cut-off point. It also includes an estimated mitigation costs, if the real cost of mitigation exceeds the prearranged amount, buyer can claim that from seller (Quastel et al., 2018). In the UK, a Radon Retention Bond is held by the purchaser or in trust by a lawyer. After the busy transaction done, a radon test is done in a suitable time and the bond is used to pay for the mitigation, if needed. If not, the fund is sent back to the seller (BRE Global, 2018). In Canadian province of Alberta and New Brunswick, respective real estate council and realty association acknowledge and encourage such measures. In New Brunswick, a buyer is advised to negotiate an amount for mitigation to put in trust by stating in the seller agreement should the radon test be done after the transaction made (New Brunswick Real Estate Association, 2018). Likewise, the Real Estate Council of Alberta (2019) suggests potential buyers to keep a holdback term contingent on reliable testing and mitigation, if necessary; where the seller has not tested for radon.

We identified some population health determinants like education, income, occupation, social connections etc., to be crucial in getting access to radon health risk information. To this end, the issue of radon health risk can be *included in the public health risk awareness program* *as well as school curriculum*. Federal plan to test workplaces covers only the government offices; this can be expanded as a mandatory provision to the private offices and workplaces by making inclusions under the *workplace safety and industrial hygiene laws and regulations.* Education and training of people involved in construction, building and real estate industries are also important. As an example, the New Brunswick Real Estate Association (NBREA) requires realtors to take a radon course that teaches them about the dangers of radon and different radon mitigation methods. Besides, such training currently requires that realtors of both the seller and buyer mention radon during a real estate transaction (Quastel et al., 2018).

The government of Canada's poverty reduction program that is supporting low-income groups with financial supports can be tailored to focus on public health issues like financial support for testing and mitigation of indoor radon. In addition to the population health determinants, there exist a group of environmental – geographic, geologic, climatic and atmospheric determinants that impact residents' exposure to radon gas and its progenies. Thus, there is a need to involve and engage other sectors and disciplines in order to launch a holistic population health intervention approach.

Therefore, we argue that following *Rose's population strategy of prevention*, shifting the distribution of a risk factors to the entire population could lower everybody's risk and reduce the overall prevalence of radon-induced lung cancer (Schwartz & Diez-Roux, 2001). To this end, radon management plan has to be scaled up to address the determinants that enable and hinder residents' adaptive actions. Thereby, the population distribution of the risk can be shifted from certain vulnerable group and regions that will lower the overall incidence of lung cancer cases at the population level. Implementing such broad-based intersectoral policies and programs are challenging and such an effort needs support from all relevant partners. This policy aspect is discussed in the next section.

Limitations

As it was out of the scope of this study, we did not use health inequity toolkits to measure the absolute and relative differences in the level of risk perception among population sub-groups. It was due to lack of adequate population-level data. As mentioned separately under both the quantitative and qualitative studies, our studies are limited by sample size and locations covered. The survey conducted online might have failed to include participants from diverse demographic and cultural backgrounds, which might have skewed our results. Particularly, in the Ottawa-Gatineau areas where the education level is higher than any other regions of the country as reflected in our sample. Besides, there were employees (ex and current) of the federal government, especially people who had friend from Health Canada- these created the opportunity for them to learn more about radon compared to other citizen living in different parts of the country. Thus, as already said, future research could generate robust data from a representative sample and interviewing with participants from diverse socioeconomic backgrounds and covering high radon areas in Canada. Notably, similar studies in cities of active radon health communication interventions would generate noteworthy evidence to support or counter the findings of this study.

Chapter Nine: Policy Analysis and Recommendations

This section discusses the final research question related to the application of evidence gathered: ***What are the policy recommendations based on the evidence collected?***

As we have discussed, radon guideline issued by the federal government is voluntary and it assumes that residents would act rationally according to the provided information (Health Canada, 2014). Besides, the building codes are not obligatory in all jurisdictions, particularly in Ontario and Quebec (Dunn & Cooper, 2014). There is an incongruity within the scientific community concerning radon risk management policies in Canada. First, despite evidence that setting the reference level to 100 Bq/m^3 as recommended by the World Health Organization (2009) would save more lives (Peterson, Aker, Kim, Li, Brand, & Copes, 2013), the level is still 200 Bq/m^3. Second, although research has determined that there is no safe threshold level for radon and any level of exposure can lead to the development of lung cancer (Darby et al., 2005; Turner et al., 2011), application of the guideline has not changed accordingly.

As we observed in different countries, enforcing radon guideline and enacting building codes without considering residents' views and consulting key stakeholders did not work. Therefore, in this section we are concentrating on the interdisciplinary theoretical connections between the findings of this research project and policy implications that will work in the Canadian context.

The scholarship that links science to decision making embraces at least three disciplines such as knowledge translation (science communication), risk communication, and policy or decision analysis (Winterfeldt, 2013). The mixed methods study we conducted, identified specific examples of the interdisciplinary and inter-sectoral challenges that surface while addressing the factors influencing exposure to radon health risk. From a population health perspective, we examined the determinants of health and primarily the social determinants of health that closely affected residents' decisions. In addition, our study found the leverage point of health communication where to emphasize while designing radon health risk communication program. We also identified the factors that enable and obstruct residents to take the preventive and adaptive actions. These enablers and barriers are the root causes of either motivation for action or inaction residents take to prevent the health risk.

Earlier, we briefly discussed some policy models, frameworks and theories concerning radon health risk in the initial scoping review. Here, we discuss in more details how these can be applied in reforming and/or implementing national radon policy in Canada based on our findings from both the quantitative and qualitative studies.

Although science usually helps decision makers by influencing their perception and beliefs with evidence, the case of radon health risk is unique with a lot of differences in the ways people usually think of a risk. There is a dilemma with the radon health risk. On one hand, decision makers are prone to see the immediacy of a hazard and emergence of a threat – i.e. how many people are affected or dying in a short period. On the other hand, holders of scientific knowledge often do not understand this type of information need of the decision makers. So, we tried to explain this phenomenon with some relevant frameworks.

Framework to Bridge Science and Decision Making

Winterfeldt (2013) provides an illustrative example in this regard and draws a framework to bridge the information gap between science and decision making. In relation to personal health decision making, he demonstrates how a medical decision is made upon exchange and interaction of information between a physician and a patient. In one side, there are scientific inputs along with an academic or institutional credence assumed by a physician, and on the other side, there are beliefs and values held by a patient -the decision maker in this case. The example illustrates the ways the opposing beliefs interact, make trade-offs based on scientific logic as well as values and real-life constraints to mutually dissipate uncertainties in order to reach an acceptable decision. Such decision analysis facilitates policy adoption by building bridge between scientific knowledge and decisions. Therefore, decision analysis is a useful process that demands analytic skills as well as mutual understanding. The framework in Figure 16 below illustrates the pathway of building a bridge between science and decision making.

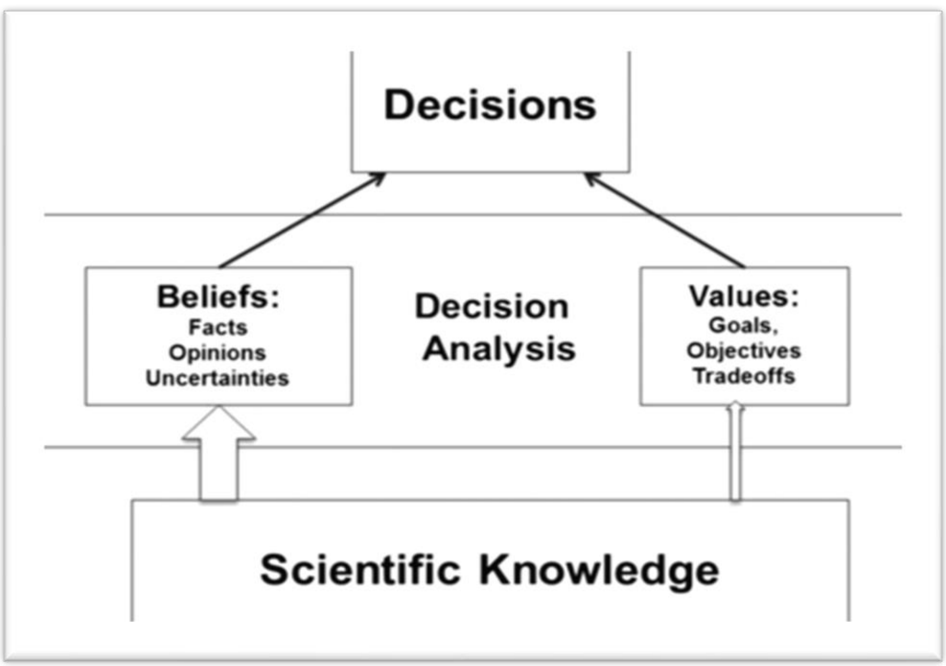

Figure 16. Framework to Bridge Science and Decision Making

(Winterfeldt, 2013; reproduced with permission)

The majority of decision-making theories assume that any decision made is based on two fundamental pillars - beliefs and values (Figure 16). Beliefs reflect a decision maker's perception about the reality that includes facts, opinions as well as uncertainties. Science can inform belief that is grounded in logic, but not belief that is founded merely on dogma. On the other hand, values reflect a decision maker's sense about something that is worth to strive for and accomplish. It includes ones' goals, objectives, and associated trade-offs. The two groups of theories present in decision theories include the a) *prescriptive* ones such as expected value theory (Dietz, 2013), expected utility theory (Nau, 2007), expected regret theory (Tsalatsanis, Hozo, Vickers, & Djulbegovic, 2010); and b) *descriptive* theories such as prospect theory and cumulative prospect theory (Kahneman & Tversky, 1979).

The descriptive prospect theory from cognitive psychology involves the mechanism through which people choose policy options from the probabilistic alternatives that include risk, where the probabilities of outcomes are uncertain (Tversky & Kahneman, 1992). In our case of radon, as extensive evidence has removed uncertainties about the outcomes, we are going to discuss here the first category of prescriptive expected utility theory.

As mentioned above, the decision curve analysis (DCA) is a widely used method for evaluating diagnostic tests and predictive models in medical and pharmaceutical domains. It was developed based on expected utility theory (Nau, 2007) and has been reformulated using expected regret theory (Tsalatsanis, Hozo, Vickers, & Djulbegovic, 2010). Under certain circumstances, these two formulations yield different results. Where the expected utility theory considers the highest expected value for the best course of action, the expected regret theory looks for a decision that will lead to the least amount of regret.

We can apply these theories to our radon mitigation situations and explain the variant outcome in low radon level areas. In our first case, we consider ventilation has an effectiveness of 40% (probability 0.4) of radon mitigation. We assume that it gives an extra year of fulfilled life when effective and has no impact in the life course when it fails (probability 0.6). Thus, we can anticipate the value of this mitigation system to a young resident. The expected value is measured as the sum of the value of each potential outcome multiplied by the probability of that outcome occurring. We have two outcomes in this case: success and failure. Therefore, the expected value = [(0.4 x one year of fulfilled life) + (0.6 x 0)] = 0.4 years of fulfilled life. When assumed that each additional life is equally valuable to us, expected value estimation is useful in selecting between mitigation systems.

To compare, we take the sub-slab depressurization system of mitigation that has an effectiveness of 90% (probability 0.9) and it adds two years of a fulfilled life when it succeeds, but when it fails, it causes half a year loss of fulfilled life in high radon areas. Then, the expected utility of this mitigation technique will be = ([0.9 x 2 years of fulfilled life) + (0.1 x -0.5 years of fulfilled life)] = 1.8 - 0.05 = 1.75 years of fulfilled life. Therefore, the second mitigation system will likely provide 1.35 (1.75 -.4) more years of fulfilled life compared to the first. So, if the cost of SSDS mitigation is $3,000 and the ventilation system costs $2,200, funding SSDS would obviously be cost effective. This analysis supports our outcome from the systematic review that an SSDS is the best mitigation method in terms of cost-effectiveness as well. However, explaining 1.35 more years to the fulfilled life years is not so straightforward. There are psychometric properties set by the World Health Organisation Quality of Life assessment (the WHOQOL-100) to measure and explain the quality of fulfilled life meeting the culturally relevant conditions (World Health Organization Quality of Life Group, 1998) that go beyond the scope of this thesis.

Analyzing through DCA model in medical domain, Hozo, Tsalatsanis, and Djulbegovic (2018) found the expected regret theory to be preferable to the expected utility theory as i) it is mathematically more parsimonious and ii) regret is widely recognized as one of the critical decision-making mechanisms enabling a decision maker to experience consequences of decisions both at the emotional and cognitive level. This perspective matches with our finding of dual - cognitive and emotional perception of radon health risk that is conducive to the adoption of preventive measures by the residents.

Since probabilities and values are difficult to estimate, scientists have argued that people should in practice be cautious about taking these expected value estimates literally (Djulbegovic, Hamm, Mayrhofer, Hozo, & Van den Ende, 2015). Nonetheless, the above rationality goes more to the person-centred health policy decision making such as testing a home for radon or not. While thinking to affect policy in a broader population health arena, we have the options to look into wider frameworks with extended policy scope that are able to address the proximal determinants of health. We discuss such a framework next.

Milio's Framework in a Model of Prevention

Milio's framework focuses on examining the determinants of population health and on influencing those determinants through public policy. It assumes that the health status of a population is determined by the availability of too little or too much essential health sustaining resources. These include formal and informal sources of knowledge that shape people's perception, help modify practices and behavioural patterns to influence their health positively or negatively. Likewise, organizational practices that include policy decisions impact health by making resources and options available to guide citizens' health decisions.

Milio (1987) postulates that an individual's health selections are influenced by the objective to maximize valued resources. Such selections are based on the individual as well as societal resources. Thus, she argues that a cumulative change in individual health selection can gradually turn into the public opinion that will subsequently lead to a social change, and this can be made possible by strategically raising public awareness. When significant investment is made for proper teaching and learning, residents' behaviour patterns change over the course of time in favour of positive health.

Relevance of Milio's Propositions to Our Case

1. Population health results from the deprivation or excess provision of critical health resources.

2. Behaviours of population result from their selection of options from limited choices; these stem from the beliefs and expectations founded in socialization, education and experience.

3. Organizational decisions and policies (both governmental and nongovernmental) dictate many of the options available to individuals and population that influence choices.

4. Efforts to maximize valued resources influence individual decisions related to health-promoting or health-damaging behaviours.

5. Alteration in patterns of action resulting from decision making of the significant number of people in a population can result in positive social change.

6. Without concurrent availability of alternative health-promoting options for investment of personal resources, health education would be largely ineffective in changing behaviour patterns (Milio, 1987).

In light of the above Milio's framework (2007), it is understandable that personal behaviour patterns are not merely free choices of lifestyle that can be isolated from the context. Rather concerted systems level actions by the authentic agencies engaging stakeholders from different layers of the society can make the healthy options obtainable. Making such provision is possible only through greater political commitment that takes into account the goodwill of political decision makers as well as active participation of stakeholders and population of affected communities. A political model (Hall, 2007) can engage citizens to serve the purpose of raising greater awareness by creating a social climate favourable for policy implementation (Nutbeam, 2010). Hence, we discuss such a model in the following section.

Politics of Risk

Paul Slovic (1999) observed that risk management in the contemporary world has become increasingly politicized and contentious. He maintained that there are extensive polarized views with controversies and conflicts between people holding opposing perspectives. Consequently, he described a political dimension of risk and suggested that the scientific studies of risk should seek a new perspective through analyzing the complexity of the concept of risk and demonstrating the shortcomings of the traditional view of risk assessment that considers risk merely a scientific enterprise. To that end, Slovic (1999) argued that although a risk is considered significant, people's perception of that is inherently subjective as broader constructs shape that. Therefore, scientific evidence must be interpreted with the viewpoints of individuals' psychological, social, cultural, and political understanding.

Another aspect of risk politics is that the social and democratic institutions entrusted to manage risk, have a critical rule that if not appropriately discharged can generate distrust in people. The authority that governs the concept of risk should look for the acceptable solution to the problem. However, if in exercising power, they move merely by dry logic, choose only the cost-effectiveness interventions ignoring the best solution that ensures safety and security at some extra cost; then, public trust in them will be in peril. On the other hand, integrating the contextual features and public inputs through dialogue with the relevant stakeholders can create a milieu conducive to optimal risk management (Slovic, 1999).

Although health literacy and public awareness are essential, these are deemed not crucial while coming to the politics of risk. People are generally considered rational; however, their circumstantial positions play a significant role in judging a risk. Moreover, the emotional and affectual features take parts in making the final decision. Thus, despite being simple, risk management is a sophisticated process where the worldviews, ideologies, values – all have an involvement. Therefore, Slovic (1999) acknowledged the limitations of risk science and admitted the difficulties in maintaining public trust while managing a risk. Thus, considering the complex sociopolitical nature of risk management, he proposed a shift in approach while scientifically calculating the risk. Hence his suggestion is to involve and engage the members of the public in both the assessment and management of a risk. Such public engagement will make the risk management process democratic, relevant to the context as well as add legitimacy and secure public acceptance and sustainability of interventions undertaken in this regard (Slovic, 1999). A framework from political science discusses these aspects in more details.

Framework from Political Science

Theoretically, the 3-i framework from political science considers three specific actors for policy change. These are interest, idea, and institution (Hall, 1997). The 3-i framework offers a comprehensive set of variables to consider in the analysis of policy change (Lavis, Ross, & Hurley, 2002; Lavis et al., 2004; Palier & Surel 2005; Waddell et al. 2005). The scholarship upon which this conceptual framework is founded hypothesizes that its component variables interact with each other to shape policy directions (Figure 17 below). However, in the complex system of policymaking, one or more of the variables can also act independently to influence policy change. While developing and testing this framework integrating the concept of institutions, interests and ideas, Shearer, Abelson, Kouyaté, Lavis, & Walt (2016), specially considered 'networks' that impact policy change. For this purpose, they added evidence from three population health intervention studies conducted in the international domains.

Initially, they defined 'networks' as both empirically measurable sets of actors and their relationships, and as intentional governance or management structure with an agency that acts strategically. A vital challenge of those studies was whether networks, either empirical or intentional, exert an independent influence on policy change, or whether they were mere bystanders, mediators or moderators, of the causal relationship between any of the Is and policy change. Studying these complex phenomena, they shed some light on the mechanisms underlying the observed phenomena of policy change.

The first of the 3-is, is institution that is found to be the 'rule of the game' as it provides structures to the policymaking process in ways that favours some outcomes over others (North, 1990). Others consider institutions that shape future policy change primarily through the mechanisms that create and distribute incentives (Hall & Taylor 1996; Pierson, 1993). Political institutions are found to be at the core of policy change as these can provide a window for public action. Institutions may be formal or informal, but formal institutions are particularly

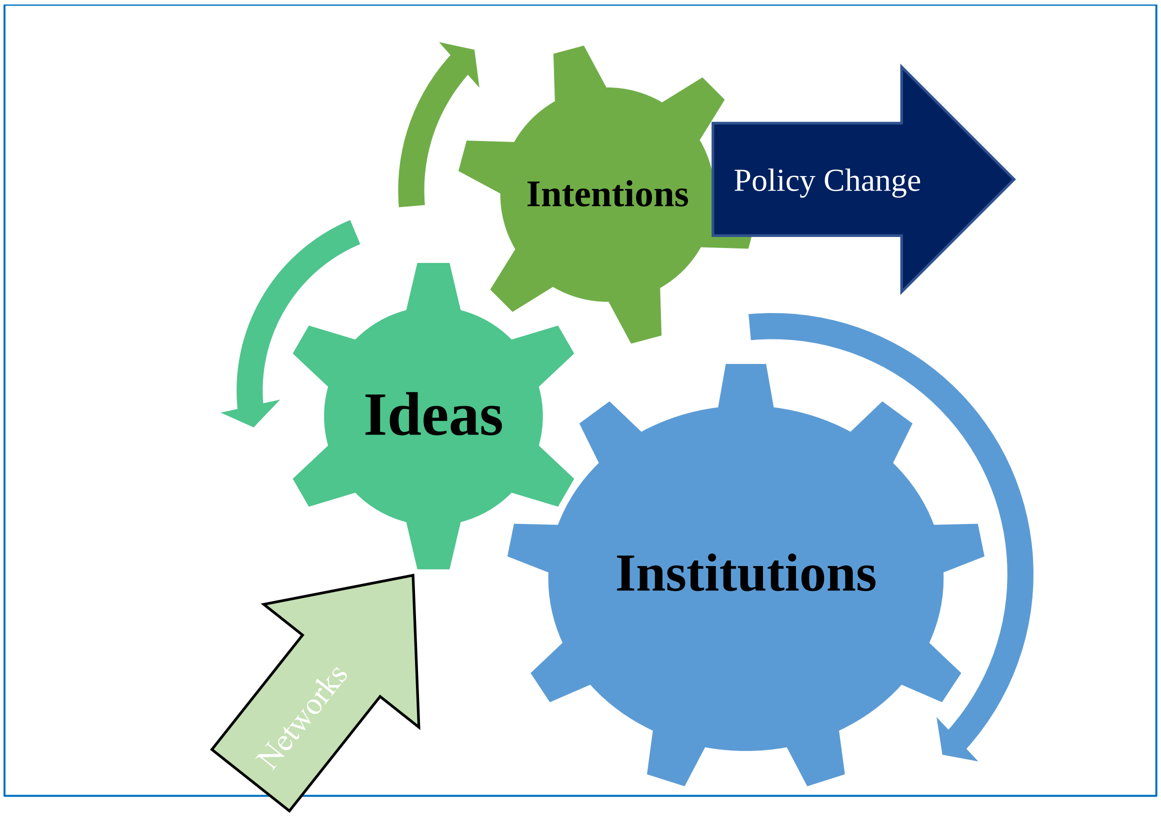

Figure 17. Conceptual Framework of 3-i and Network Variables on Policy Change

(Reproduced with permission from the National Collaborating Centre for Healthy Public Policy; NCCHPP, 2014)

pertinent in the study of policy change in the developing country settings whereas informal ones in the developed worlds. The studies found that various networks successfully influence policy change and in their relationship with institutions, they interact with it while motivated by various interests and ideas (Shearer et al., 2016).

Figure 17 above presents a conceptual framework of 3-i along with the network as it impacts policy change. Although networks can be some other institutions, they are regarded as a variable in their own right. Networks can influence policy change by arbitrating the pattern of relations among different actors that can be a more informal process than the institutions act (Marsh & Smith, 2000; Sandstrom & Carlsson 2008). However, networks are likely to change in response to institutional pressures: “a change in institutional rules directly affects network structure by creating new opportunities and incentives for policy interactions” (Lubell, Scholz, and Berardo, & Robins, 2012, p.355). Conversely, networks can create, reinforce or challenge institutions by facilitating interactions among actors in ways that might lead to the shifts in norms, preferences and power dynamics (Hall & Taylor 1996; Helmke & Levitsky 2004).

Second, interests describe the *preferences and power* embedded in policy actors (Figure 17 above). Behavioural schools of policy change assume that policy outcomes are primarily determined by actors’ interests (Hall & Taylor 1996). The ability of actors to attain and exercise their interests depends on the distribution of resources and power in a policy domain that determines actors’ capacity and skills. Most interest-based theories acknowledge the structural constraints of a particular agency. Scholars describe a growing authority of private and non-state actors in government policymaking processes by adding power to the civil society organizations in the developed country (Buse & Walt 2002; Litvack et al. 1998; Mathews 1997) and doing the same to the international organizations in developing countries (Dobbin et al.2007; Kahler & Lake 2004). Thus, the distribution of preference and power is primarily driven by access to resources in both of these settings though each has its distinctive features (Shiffman, 2014).

Networks can help visualize how interests, embedded in nodes, are structured in the policy process and how network structure changes as actors’ form and dissolve relationships among them. Like institutions, networks can influence the balance of power by choosing to include or exclude participants based on their interests (Marsh & Smith, 2000). In the other direction, actors embedded in nodes have the agency to decide who they will interact with, that can shape networks to advance particular interests (Howlett, 2002; Marsh & Smith, 2000) and control information exchange (Shearer 2014).

Third, the concept of ‘ideas’ in policy sciences is broad and relates to the content and strength of actors’ *knowledge, perception and values* in the policy process (Hall 1993; Lavis, Posada, Haines, & Osei, 2004; Surel, 2000). Ideas shape agenda-setting, policy formulation and implementation by determining which statements of the problem and options for solutions will be heard and understood by policy-makers (Hall, 1993; Sabatier & Weible, 2007; Surel, 2000). The importance of technical information and knowledge as a variable has risen as policy-making has become increasingly driven by expertise in some settings (Beland 2010). Integration of evidence to inform health policy has achieved international normative status in the past decade (World Health Organization, 2005).

Networks play an essential role in the creation, dissemination and reinforcement of ideas (Owen-Smith & Powell 2008). Ideas are exchanged over network ties, and thus the pattern and structure of relations affect the rate and reach of information dissemination (Reagans & McEvily 2003). Networks can reinforce or shift a particular paradigm and make some values more aggregable to decision maker (Sabatier & Weible 2007). There are factors like *values, preferences, experiences and knowledge* that determine how different actors may form allies and networks to impact policy. Gathering of actors around specific ideas influence the shape and power of the network. Figure 17 suggests how these variables depend on each other, specifically, when institutions provide the scaffolding for network structure, interests are embedded in actor nodes and ideas are exchanged along ties between actors. Changes in any one of these factors can be initiated by endogenous or exogenous elements and may be influenced by other dynamics through the feedback loops to generate impetus for policy change.

Application of 3-i Framework to Radon Policy Change

From our radon health risk management perspective, existing policy change frameworks can be divided into these three key elements or explanatory variables: Institutions, Interests and Ideas -together known as the '3-is'. Institutions refer to the mandated agencies responsible for formulating and implementing policies. In this context, there are three levels of governments in Canada -federal, provincial/territorial and municipal. Besides, there are collaborated research networks affiliated with the academia, and non-governmental organizations with mandate from the government to deliver particular tasks. In particular, at the federal level, Health Canada is the lead institution holding mandate for health risk policy implementation. It discharges this duty in collaboration with partners at different levels of both governmental and non-governmental organizations.

The interests relate to the stake or preference of these institutions in preventing lung cancer by exercising their authority and power of policy formulation, spending and investing resources with the aim to prevent lung cancer burden that is having a big economic toll on the health system across Canada.

Ideas are the strategies adopted under the National Radon Program as well as evidence generated by researchers and lessons learned by practitioners and partners carrying out the same mission. The same elements from the residents' side are their perceptions, suggestions and worldviews about radon health risk. The networks comprise the researchers, public health practitioners, environmental actors, radon industries and businesses, community activists and other stakeholders with related interest and values (Palier & Surel 2005).

Application of this 3-i framework in reforming the national radon policy in Canada will help to identify more partners from other sectors, domains and disciplines -those having some vested interests and values either favourable or conflicting. This includes exploring the perspectives and roles of civil society organizations that are crucial for leveraging radon health risk policy. Analyzing these variables within this 3-i framework will demonstrate the relationships among these discussed policy variables - institutions, interests, ideas and networks; thus, help to propose and test a common framework to develop a public voice for the favourable policy change. As we observed from the empirical data generated through three studies in the international domain, change is generally led by a shift in one of the 3-is, setting off events in the policy process that altered the other Is, changed the structure of the policy network, and led to policy change. Our analysis suggests a new research agenda that can continue to define the concepts and methods for exploring the integration of network variables in health policy analysis in Canada.

In Canada, there are institutions, organizations and agencies as well as active networks. Among them are CAREX Canada[2],CARST[3],Canadian Environmental Law Association (CELA[4], 2016), and Pollution Probe[5] - who have been pushing forward the policy initiatives and proposing effective laws to ensure the safety of home and work environment. CELA (2017) has been advocating for either a tax credit or a grant and argued with simple analysis that such an incentive would not affect revenue. Instead, such initiatives will save more than 17 million dollars of direct healthcare cost and return higher tax revenue from those surviving to both the provincial-federal treasuries (CELA, 2017).

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[2] CAREX Canada is a national surveillance project that estimates the number of Canadians exposed to substances associated with cancer in workplace and community environments.

[3] CARST (Canadian Association of Radon Scientists and Technologists) is non-governmental organization liaising on matters related to radon between professionals and other interested public and private organizations. It works in collaboration with the Health Canada and other agencies to advance NRP.

[4] Canadian Environmental Law Association (CELA) is a non-profit, public interest organization established in 1970 to use existing laws to protect the environment and to advocate environmental law reforms.

[5] Pollution Probe is an environmental non-governmental organization in Canada. It is working with support from Health Canada to raise radon awareness in workplace and communities, it also advocates for actions to reduce environmental pollution.

Updates on Radon Policy Initiatives in Canada

Recently, with a mandate from Health Canada, the Canadian Environmental Law Association (CELA, 2018), in partnership with CAREX Canada, conducted an environmental scan of radon law and policy at home and abroad (Quastel, Siersbaek, Cooper, & Nicol, 2018). Especially, they synthesized the best practices of radon regulations, policies and initiatives from six European countries - Denmark, Finland, Sweden, the UK, Norway and Switzerland. Their report has explored the barriers and strategic opportunities to enhance the effective delivery of the National Radon Program to improve radon health risk protection across Canada. The report summarized the current state of law, policy, and best practices including federal, provincial/territorial, and municipal responsibilities. It also provided policy recommendations with short- and longer-term policy options, pinpointing the strengths, limitations, and implementation options for Health Canada as well different levels of governments (Quastel, Siersbaek, Cooper, & Nicol, 2018). A few key aspects of that report relevant to our project are:

- In Canadian federal systems of governance, radon-related regulation, laws and policies have the form of shared responsibility.
- While the Council of European Union’s (2013) basic safety standards directive can require member states to address radon in both private and public buildings by developing radon action plans and a system of enforcement, Canadian federal guideline cannot require provincial or territorial actions, it only provides a comprehensive policy direction and encourages coordinated efforts.
- Canadian governments are not using either spending or taxation powers to financially support residents to mitigate radon while such assistance is available in countries like Norway,

Sweden, Switzerland and the UK. Such a provision could be useful for low income and Aboriginal Canadian people living in reserve housing in Canada.

- The Federal-Provincial-Territorial Radiation Protection Committee who holds the mandate to advance harmonization of radiation protection practices and standards across the country could do more by promoting radon training for certain inspectors such as those who look after compliance with building codes, occupational health and safety and public health.
- The report found the provincial/territorial governments to have the most law-making scopes concerning various public health issues of the indoor environment. These include enacting building and labour codes, real-estate warranty programs, workplace and occupational safety laws, residential tenancies and occupier's liability, public health requirements of school and childcare facilities etc.
- While most provinces updated building codes and Manitoba even exceeded the national standards, Ontario and Quebec, focus areas of this study, lag in terms of enforcement and modernization. For example, in Ontario, although the Building Code applies throughout the province, the radon-related provisions are limited and applicable to only three defined areas- the towns of Elliot Lake, Townships of Faraday in Hastings County and Hyman in the Sudbury District (Dunn & Cooper, 2014).
- However, Ontario is currently under the process of updating the building codes incorporating radon-related provisions that are to reflect the National Building Code and extend the province-wide coverage. Under this new code, buildings are to be designed and constructed to keep the radon level below the federal guideline of 200 Bq/m^3 on an average annual basis, and this will lead to mandatory testing of buildings for radon to confirm compliance with radon

requirements. It was to enter into force by January 2019 (Ontario Ministry of Municipal Affairs and Housing, 2017). However, the legislative process is still ongoing.

- However, within this provincial policy vacuum in Ontario, several municipalities have enacted stronger codes, these include the City of Guelph Central Elgin, Saint Thomas, and Thunder Bay. They all require builders to meet radon prevention measures into all new residential buildings. Similarly, the Council of Southgate Township and Municipality of Grey Highlands have recently approved by-laws for the implementation of a Radon Gas Mitigation Program under Section 9.13.4.1(1) of the OBC (Ontario Ministry of Municipal Affairs, 2016).

- In Quebec, amendments to the Quebec Construction Code (QCC) came into force in June 2015. It included some elements of the National Building Code relating to radon measures with some specific changes exclusive to Quebec and enforced as of December 2016. However, the province chose to ignore certain updated radon-protection measures in the National Building Code including keeping the previously set reference level 800 Bq/m^3 of 1987. However, the Association de la Construction du Québec recommends that builders should follow the National Building Code (NBC) 2010 to address radon problem. Likewise, the Régie du bâtiment du Québec authorizes municipalities to establish their by-laws with firm radon requirements and several municipalities have already done so or are planning to do so. These include Ascension, Chelsea, Oka, Notre-Dame de Pont Main, La Pocatière, Saint-André-d'Argenteuil, Saint-Colomban, Saint-Hilaire, Saint-Pierre Île d'Orléans and Vallée-de-la- Gatineau. Thus, radon regulations differ from municipality to municipality in Quebec (APCHQ, 2018).

- As per the Quebec provincial authorities, they are to adopt the complete version of radon preventive measures as enshrined in the National Building Code in the next revision of the

Quebec Construction Code. However, it is not yet certain when these will come into effect (APCHQ, 2018).

Ethical Principles in Policy Implementation

As discussed briefly in the initial literature review, like other public health issues, the implementation of radon health risk management policy requires a satisfactory ethical reflection. From the environmental epidemiological perspective, Pagliarani and Botti (2011) provided moral insights regarding the transparency of communication of research findings and the values of precautionary principles.

Communication and transparency. The first ethical aspect relates to the duty of researchers to report research outcomes with accuracy and transparency as these are aimed to improve the health of individuals and conditions of the communities. Here, it is assumed rather a prerequisite that research is conducted in a scientifically sound way, published and peer-reviewed before presenting to the affected communities or individuals as well as to colleagues and scientific community in general. The validity and reliability of data, unambiguousness of the findings (with the degree of uncertainty and not withdrawing any information), clarity of the evidence (whether it applies to the community as a whole or can relate to the health of individuals) and visibility of the communication approach - are all crucial. Any lack of transparency will be a detriment to the ethical principle of autonomy as both individual and community have the right to make an informed decision about their health after a full understanding of the risk. An important point is the fundamental freedom of study participants. The protection and honour of their liberty should not be limited to only the start of a study by taking consent, but this should be maintained as a moral commitment till the end by communicating the study outcomes clearly and accurately. Another point in the communication is that researchers should clearly express how much their values, beliefs and experience played roles in the interpretation of the produced research outcomes (positionality and reflexivity as described before). It is critical when there is a degree of uncertainty in the results. Researchers are suggested to behave consistently with their ethical-scientific position and be ready to express it. Such an attitude encourages proactive information sharing that in turn, inspires study participants' active engagement in policy dialogue. Thus, it favours autonomy and liberty of choosing from the available options (Pagliarani & Botti, 2011).

Principle of precaution. The value of the precautionary principle in risk evaluation domain is internationally recognized. It has been taken as a guiding principle in the United Nations Conference in Rio de Janeiro on Environment and Development in 1992, the Cartagena Protocol on Biosafety in 2000, the 2001 Stockholm Convention on Persistent Organic Pollutants (POPs) and the London Convention of 2001 on anti-fouling paints (Botti, Comba, Forastiere, & Settimi, 1996; Botti & Comba, 2003). The distinction between the principle of precaution and that of prevention resides in the degree of uncertainty of an adverse health effect. While the principle of prevention is applied to the established risks, the precautionary principle relates to the management of undetermined risks. In general, the precautionary principle states that a lack of sufficient scientific certainty should not be a reason for postponing the implementation of a useful preventive measure to contain a hazard, when it deems reasonable, not necessarily so; thus, it reverses the burden of proof (Martuzzi & Tickner, 2004). The proponents of this principle intend to be on the safe side rather than be sorry by acknowledging the potential of a risk from some exposure. They do not accept the notion of those who do not want to intervene; thus, victimised by the risk.

However, in environmental epidemiology, the ‘zero risk’ hypothesis does not exist. Uncertainty is not determined by any assumption or opinion; instead, it is still based on the interpretation of data. Thus, uncertainty pertains to the inability of a study to measure risk; it is not the uncertainty of the existence of the risk. Therefore, an uncertain risk is still a risk that needs attention as adverse health effect can still occur. This precautionary principle does not apply to radon as many epidemiological studies have already established the causal relation of lung cancer to radon exposure. However, some proponents (Botti & Comba, 2000) of the precautionary principle invoked it to health risks that are different from that of uncertainty, but the concern is confined to a small, well-defined group of people. In such cases, the preference is given to the benefits of health of that group as well as the economic benefit of the entire community. In this regard, when we consider over 3,200 radon-induced lung cancer deaths in Canada and put the monetary value of avoiding the loss of life, the estimated economic loss becomes $22,400M (3200x7M; Mishan & Quah, 2007). Therefore, from an economic perspective taking preventive action should be considered.

Social justice. The most important ethical principle of radon health risk management relates to social justice. The reason behind is that we have noted an issue of unequal distribution of the risk as evident from differences in residents’ risk perception and their ability to manage it. Keeping these in consideration, radon health risk management strategies should: a) Design a fair, transparent and participatory process of decision-making so that it is unbiased and objectively covers all the vulnerable houses as far as possible. b) Look for solutions that can be implemented with the limited risk management resources to maximize the benefit for those who are in need. c) Any strategy adopted should not increase the equity gap instead close it as far as possible.

Besides, the ethical principle of autonomy requires that residents should be provided with the necessary information and they should be involved in decision-making (Barrett, Stiles, & Patterson, 2012). Another aspect is to remain flexible to accept any new scientific development in the field, revise and improve the strategy accordingly. Finally, there is need to be cognizant that complete elimination of radon risk will never be possible even after installing the best mitigation technique and implementing all possible interventions.

The World Health Organization's Guideline

In 2009, the World Health Organization published the 'WHO handbook on indoor radon: A public health perspective.' This handbook provides policy guidelines to reduce health risks from exposure to residential radon that includes disseminating information on indoor radon levels and related health risks. One of the options was to execute a national radon program with the objective to reduce both individual and overall population health risk in high radon areas. Another was to set a national annual average radon reference level to 100 Bq/m3, with the option where this level cannot be reached under the current country contexts, the reference level should not exceed 300 Bq/m3. Among other recommendations were enacting building codes during construction that prevent radon from entering homes, implementing programs that ensure radon levels are below the national reference levels and developing radon measurement protocols that can assure quality and consistency in radon testing (WHO, 2016).

In Canada, Health Canada launched the radon awareness program since 2007. Most provinces incorporated radon regulations in the building codes and some provinces and territories updated building codes by 2017. November is observed as the National Radon Action month since 2013 (Government of Canada, 2013). However, despite evidence in favour, Canada has not yet set the radon guideline at the WHO recommended level of 100 Bq/m3.

ICRP Recommendation: Optimization Principle

Vaillant & Bataille (2012) reviewed the past and current ICRP publications dealing with the management of radon exposures to identify the significant factors considered by the Commission during the last 50 years in improving the management of radon exposure. They revealed substantial improvement since 2009. Before that, in 2007 ICRP Publication 103 (Ann. ICRP 37, 2009) advised to consider the action levels and mitigate only when exposures exceed these levels. However, later the Commission revised its approach to propose that radon exposure should be managed by applying the optimization principle and mitigation should be done at any level (ICRP, 2010). However, as far as the assessment of the radon risk is concerned, it appears that the successive changes made by ICRP (2010) did not have a substantial impact on the values of radon gas concentration recommended as action levels either in dwellings or workplaces. The significant change occurred in late 2009 with the publication of the ICRP Statement on Radon, which acknowledged that the radon risk had been underestimated by a factor of 2, thus encouraging a significant revision of radon reference levels (Vaillant & Bataille, 2012).

Policy Implications

In light of the above, our recommendations for Health Canada, the lead agency trusted with the responsibility of radon health risk management program in Canada, are the following:

a) There is a need to take concerted policy actions to address the radon health risk in an integrated manner linking efforts at all levels by developing a common agenda, goals and objectives. To this end, *a national radon testing and mitigation framework convention* should be established under the auspices of Health Canada and followed thoroughly by all partner agencies and organizations at all levels of governmental and non-governmental initiatives.

b) There should be state-of-art public service risk communication materials in the mass media using video scripts and infographics to demonstrate the risk in real-life scenarios, for example, how children and women are exposed to radon gas living in the basement and passing most of the time indoors.

c) Health professionals, particularly physicians and healthcare nurses can be engaged with patients who smoke or are exposed to second-hand smoking to raise awareness about the increased risk of lung cancer from the synergistic effect of tobacco smoking.

d) Health Canada can engage public health professionals including public health nurses and dentists, environmental health professionals, public health inspectors through their departmental or organizational mandates to support raising public awareness through their professional activities.

e) There should be an established research network on radon with its hub at Health Canada. Radon mitigation interventions based on the new building codes should be rigorously researched for the effectiveness and efficiency remaining open to refining the codes and existing technologies whenever and wherever better evidence and options are available.

f) Health Canada can explore research partnerships with the building design, construction and energy sectors.

g) A potential risk exists even from the exposure to low doses of radon progenies usually found in Canadian residential houses that can initiate damage on DNA. Therefore, radon should be mitigated to keep the level as an ALARA (as low as reasonably achievable) substance.

h) There is a need to consider lowering the reference level of radon to the World Health Organization's guideline level of 100 Bq/m^3. As mentioned with reference to scientific evidence, the benefit in reducing radon-induced cancer mortality would be double and even four times higher if the level is put down to 50 Bq/m3 (Peterson et al., 2013).

i) As determined with systematic review, putting a passive radon control system (membrane plus sub-slab depressurization pipes) during all new construction should be made mandatory that can be activated whenever indoor radon level goes above the cut-off point. Likewise, an active SSDS should be placed in all existing houses where the guideline level is above 200 Bq/M^3 along with sealing of all radon entry points in the foundation.

j) Certified professionals should conduct all tests and mitigations. An accredited body from the provincial/territorial government should ensure compliance of certification. There is also a need to train people of the construction industry about radon mitigation systems.

k) The federal government should assist in radon mitigation through the provincial and territorial governments.

l) A percentage of the mitigation cost should be granted based on the total household income upon submitting the radon test results with a quote for mitigation from the certified radon professional (CELA, 2017; Quastel et al., 2018; Warkentin & Curry, 2018).

m) Residential Tenancy Act should have the provision for renters to see whether the house has been tested. If the test result found radon above the guideline level, installing a proper mitigation system would be the responsibility of property owners.

Possible Discussion Questions

1) How is the exposure to indoor radon gas a public health problem, and why might policymakers want to allocate tax money to address this risk?

2) What public health concerns would you have about exposure to outdoor radon?

3) Beyond health risks, what are some social or psychological issues raised by the residents of your target areas and how might these influence policymakers and voters?

4) Are the existing laws and regulations not enough to address the indoor radon health risk in Canada?

Chapter Ten: General Conclusion and Future Research Directions

General Conclusion

Adopting a population health approach, the initial scoping review analyzed the determinants that impact residents' exposure to radon health risk. Past research has clarified the gravity of health risk from exposure to radon progenies even at a concentration below the current reference level. The review gathered evidence known thus far, and identified which preventive measures worked, and which parts of the guideline were not consistent with the latest scientific developments. It also discussed why the NRP has not been effective and identified potential structural and socioeconomic determinants that can be explored to understand the risk in more detail. A focused literature review further clarified the relevant variables and constructs.

The qualitative pilot study provided an initial opportunity to talk with the residents and allowed exploration of some constructs related to radon health risk, especially the concern about the health of children relating to the motivation for testing and mitigation of houses for radon. It also helped developing a survey questionnaire. In the quantitative research, we tested the hypotheses in a Canadian context that residents' higher levels of perceived susceptibility, severity, synergistic risk perception, smoking in the home, care for children and social influences are significantly associated with the intention to test for radon. We found that these perception variables markedly predict resident's protection behaviours regarding testing and mitigating their homes. Thus, applying the protection motivation theoretical lens, we statistically determined that residents' perception of the health risks of radon is a significant marker of intention to test their homes for radon and a clear predictor of actual risk mitigation behaviours. However, the variables reflecting public perception of the radon health risk did not always result in the adoption of protection behaviours. To understand that aspect we conducted a qualitative study.

The qualitative study explored the vital aspects of residents' knowledge and views of radon and perception of the risk. This study filled the scholarly gap on views and perception of radon risk in Canada by providing a deeper look into residents' experiences, thus generating information that explained or complemented the quantitative results. Our study showed that many people do not get the crucial information on radon while some hold misconceptions about the health risks of radon even after being exposed to the risk information. We were able to identify the reasons behind the gap between risk awareness and actual adoption of preventive action. These were the barriers from residents' perspective that hinder testing and engaging in protective action, even after receiving the pertinent information.

The mixed methods analysis added further insight to our understanding by triangulating, comparing and contrasting both the qualitative and quantitative findings. Thus, we came to clearly identify that residents who had children living in their basement and who had significant social influences became concerned and proactively tested as well as mitigated their houses for radon. We were also able to explore the social antecedents such as health consciousness, universal care for family, type of self-education, active social networks, financial capability that determine residents' views and lead them to adopting preventive behaviours.

In our systematic review, we identified duly tested and sustainable radon mitigation systems that can effectively reduce radon in new and existing houses. We concluded that the most effective construction solutions and radon mitigation systems either for the new construction or existing homes are the combination of barrier membrane and active SSDS (sub-slab depressurization system) with sealing and caulking, respectively. The best time to test a home is late fall (from October to December). While installing the mitigation system, some factors are worthy of consideration such as the initial radon level, age and design of the house, geographic location, underlying bedrock and soil conditions, water drainage system, climate and atmospheric conditions of the area. The review indicates that even in high radon areas, effective mitigation of indoor radon can be achieved with a combination of house-specific long-term stable mitigation techniques. As there is not enough evidence about the long-term viability of any radon remediation technique, periodic radon measurement is recommended after remediation to ensure that the concentration continues to be within the acceptable levels.

Finally, the policy analysis from the individual and population health viewpoints indicated that a concerted effort is needed to address the identified determinants so that improvements are realized, especially among the vulnerable underserved population. The agencies and organizations should reflect on the overall perceptions of residents and absorb them into their mandates to be able to launch effective risk communication campaigns that can raise public awareness and motivate them for remedial actions. The pro-equity policy should effectively target and provide support to the people of low socioeconomic groups living in high radon areas so that their risk threshold is reduced to the average population level. Responsible agencies and organizations must be committed to working together with the communities, stakeholders and partners so that maximum benefits are obtained with the minimum available resources; and thereby, the population health goals are achieved. Thus, evidence-informed, responsive, collaborative, and sustained systems level actions are the best strategies that will not only bring the risk under control in this country but also will improve the overall quality of life for communities across Canada.

Take Home Message. Our study underscores the importance of seriously considering how radon risk is understood and dealt with by residents. The study empirically established that having mere cognitive risk awareness is not enough to prompt preventive action; instead, additional affective awareness motivates residents to take preventive actions. Thereby, concluded that the radon health communication program would be more effective through addressing both these aspects of risk perception along with plausible regulations and necessary incentives.

Future Research Directions

Building on the findings and overcoming the limitations of this study, future research directions would be to include a representative sample from entire Canada or at least from the high radon areas marked in the radon map to explore radon health risk perception as well as to measure other areas of interest related to this public health risk as follows:

Research on radon health risk psychometrics. There is a need to explore the dual aspects of radon risk perception applying psychometric measurements. This will help discover the facets of cognitive and affective aspects of risk perception regarding radon health risk. The quantification of the impacts of each element of risk perception on motivating residents to adopt preventive health actions will help to design the effective risk communication messages.

Radon health risk communication. Assessing residents' reaction to the content of health risk communication messages using artificial intelligence and social media can help to gather evidence about the impact of risk communication campaigns.

Radon health awareness and promotion. There is a dire need for health awareness campaigns at the community level to promote public perception about the radon health risk with the specially tailored health message. The adapted health message should have elements to address both the cognitive and affective aspects of risk perception. To this end, a participatory action research model can engage community groups and members in self-testing homes for radon. This will help to explore the issues related to low perception, misconceptions, lower level of testing and mitigation rates and thus, fill the evidence gaps in this area to find the answer to the question why residents are not proactively taking preventive actions.

Radon program evaluation research. A dedicated program evaluation research targeting the National Radon Program can explore the reasons behind low uptake of the program. This can assess the effect of mass media and impact of current risk communication messages; thus, help to identify the gap between residents' intention to adopt health action and actual action taken for radon health risk mitigation in Canada.

Cancer prevention research. The radon-induced lung cancer is preventable through modifying behavioural, structural and environmental factors. Research targeting the exploration of such factors could identify evidence to change residents' behaviours, building designs and other ecological determinants that enhance the risk; thus, can prevent lung cancer induced by the exposure to radon gas.

Radon health inequity. Measuring and understanding health inequalities is a critical first step towards informing action to improve health equity by eliminating unfair and avoidable differences in exposure to a risk and its resultants health implications (CIHI, 2019). Adopting a health equity lens, future research can assess the distribution of radon health risks by considering stratification by age, gender, education, income, geographic location, and other population sub-groups (such as Canadian Aboriginal communities and visible minorities).

Radon policy research. Study on policy implementation can examine builders' compliance with the updated building codes. The impact of enacting building codes in certain jurisdictions can be compared to other areas where the codes are voluntary. The effect of such policy implementation on the reduction of radon-induced lung cancer prevalence and mortality at the population level can be assessed in a time-series study. Different factors influencing policy implementation can be considered, and a computerized simulation can estimate the contribution of individual and cumulative impacts of such elements to the outcomes of the risk. Such approaches can support evidence-informed pro-equity policy refinement and identification of leverage points for additional interventions.

Geogenic radon potential (GRP) mapping. The current radon map of Canada was developed based on the interpolation of US data. Geospatial analysis of lung cancer incidence versus radon gas exposure can consider the influencing and interacting determinants using radon test data from the cross Canada radon survey. Such research can develop a Canada-made radon map to authentically identify the lung cancer risk of a population living in a particular geographic areas in Canada. Development of geogenic radon potential maps of Canada through the incorporation of GeoAI (geographic artificial intelligence) and systems science analyses can explore the significance of location intelligence as well as its connection with other determinants in measuring radon health risk.

Artificial intelligence in risk assessment and prevention. Public health informatics and artificial intelligence in population health represent promising approaches for risk assessment and management. This can be done by developing a macro program incorporating all the identified parameters that influence radon health risk to measure the real-time probability of exposure to a particular level of radon gas in a specific place and time, and estimation of possible consequences at a future point in time.

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Glossary of Terms

Action Level: Action level or reference level or guideline level indicates the minimum threshold level of a harmful or toxic substance which requires action (Health Canada, 2000).

Becquerel: The Becquerel (English: /bɛkəˈrɛl/; symbol: Bq) is unit of radioactivity in the system international (SI). One Becquerel is the amount of radioactivity where one nucleus decays per second (IAEA, 2019)

Concentration: The activity of radon gas in terms of decays per time in a volume of air. The unit of radioactivity concentration is given in Becquerel per cubic metre (Bq/m3) (WHO 2009).

Deoxyribonucleic acid (DNA): is a molecule composed of two chains that coil around each other to form a double helix that carries the genetic instructions used in the growth, development, functioning, and reproduction of all known living organisms.

Equilibrium Factor: This is a measure of the degree of radioactive equilibrium between radon and its short-lived progenies.

Radon Progeny: Radon is constantly decaying and giving rise to radon progeny. These are short-lived and decay until reaching a long-lived isotope of lead.

F-factor: This is used to describe the ratio between radon and its progeny. An F-factor of 1 means equal amounts of radon and its progeny. An F-factor of 0.4 is taken as representative for homes (WHO, 2009).

Exposure, Concentration and Dose Units: The exposure unit for long-lived alpha radionuclides is Becquerel per cubic meter per hour (Bq h/m3). The concentration for residential radon is expressed as Becquerel per cubic meter (Bq/m3). The unit dose used for external gamma radiation is the millisievert (mSv) (ICRP 2010).

Health Equity: The concept of health equity denotes the absence of any avoidable differences in health that are unfair and unjust due to gender, social class, occupation or in any other determinants of health within the population sub-groups (Braveman & Gruskin, 2003; Whitehead, 1985).

Mitigation: Mitigation is the process of making something less severe or less intense.

Population Health Intervention: Population health intervention refers to upstream policy and program actions that operate with other sectors and act on targeted social determinants of health aimed to reduce inequities in health outcome with the potential to improve the overall health of the population (Ghosh et al., 2011).

Psychometric: Psychometric is the field of study that applies theory and technique of psychological assessment including the measurement of individuals' differences in knowledge, attitudes, abilities etc. (Slovic, 1992).

Radioactivity: It is measured in Becquerel (Bq). A unit of Becquerel corresponds to the transformation (disintegration) of 1 atomic nucleus per second (WHO 2009, IAEA 2019).

Radon concentration: It is the activity of radon gas when it decays or transforms per unit time in a unit volume of air. The radioactivity concentration is given in Becquerel per cubic metre (Bq/m3) (WHO 2009, IAEA 2019).

Remediation: Environmental remediation refers to reducing radiation exposure, for example, from contaminated soil, groundwater or surface water. The purpose is more than just eliminating radiation sources; it is about protecting people and the environment against potential harmful effects from exposure to ionizing radiation (IAEA, 2019).

Social Determinants of Health Approach: An approach that considers the structures and systems within which people are born, grow, work and live as opposed to understanding their health separately from their sociocultural, political and historical backgrounds (Marmot et al., 2008).

Social Gradient: Social gradient in health denotes inequalities in population health status that are related to inequalities in their social status (Kosteniuk & Dickinson, 2003).

Thematic Analysis: Concerning other qualitative analytic methods that search for themes or patterns, and in relation to different epistemological and ontological positions, thematic analysis is a method for identifying, analyzing and reporting patterns (themes) within data (Braun & Clarke, 2006).

Appendices

Appendix 1. Ethics approval from the REB, University of Ottawa

File Number: H10-17-03 **Date (mm/dd/yyyy):** 12/13/2017

Université d'Ottawa University of Ottawa

Bureau d'éthique et d'intégrité de la recherche Office of Research Ethics and Integrity

Certificate of Ethics Approval

Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

First Name	Last Name	Affiliation	Role
James	Gomes	Health Sciences / Interdisciplinary School of	Supervisor
Samia	Chreim	School of Management / School of	Co-Supervisor
Selim	Khan	Health Sciences / Interdisciplinary School of	Student Researcher

File Number: H10-17-03

Type of Project: PhD Thesis

Title: A Population Health Approach to Radon Health Risks: Perception of Ottawa Residents

Approval Date (mm/dd/yyyy) 12/13/2017

Expiry Date (mm/dd/yyyy) 12/12/2018

Special Conditions / Comments:
N/A

1

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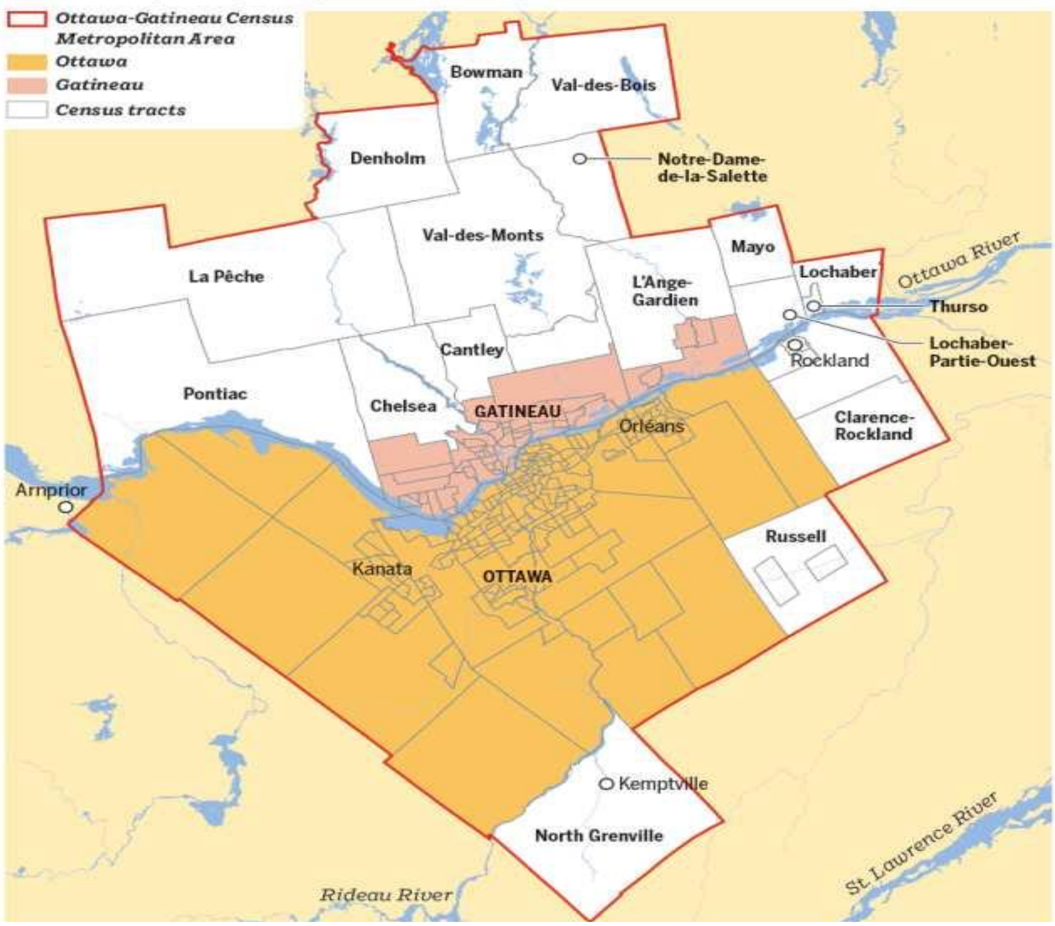
http://www.recherche.uottawa.ca/deontologie/ http://www.research.uottawa.ca/ethics/index.html

Appendix 2. List of variables and construct measured in this study

Radon Health Risk Awareness: How do residents perceive the risk?	**Source:** Where do residents look for radon health risk information, level of radon health risk awareness **Level of knowledge:** What are residents' levels of radon health risk knowledge and awareness **Types of Awareness:** **Cognitive:** Theoretical knowledge and perception of the risk
	Affective: Emotional realization that a member of family or children can be adversely affected by the risk
Radon Health Risk Perception	**Probability:** The sense of susceptibility or vulnerability that radon may present in home.
	Severity: Understanding of the adverse health effect of the risk
	Synergistic Risk Perception: Knowing that the combined risk from exposure to radon and smoking is more than that from any single exposure
Smoking History	**Current smoker:** People who smoke at present **Ex-smoker**: People used to smoke before but already quit for over six months **Never Smoking:** Never in the past life course had the habit of smoking
Social Influence	A resident came in contact to a friend, neighbour or relative who told about the risk; or such one was seen to have taken some preventive actions i.e. testing or mitigation
Care for Family and Children	Having concern for a child living in the basement to contract radon-induced lung cancer.
Enablers and Barriers	The factors that facilitate and constraint in the context of residents' adoption of preventive actions
Protection Behaviors	**Positive Adaptations:** Having tested one's home and/or mitigated for radon **Testing**: Test for radon done with following the due process guideline of Health Canada **Mitigation**: A proven mitigation system was installed with a certified radon professional
	Maladaptive Behaviors: Taking some actions that are not recommended or among the best practice guidelines or adopting a wrong measure **Denial**: Refusing the existence of radon in home

Appendix 3. Map Ottawa-Gatineau CMA (Census Metropolitan Areas)



Ottawa-Gatineau CMA (Source: Statistics Canada, 2016a)

Appendix 4. Sample size calculation

Sample size calculation: Screen print from webpage

Inference for Proportions: Comparing Two Independent Samples

Choose which calculation you desire, enter the relevant population values (as decimal fractions) for p1 (proportion in population 1) and p2 (proportion in population 2) and, if calculating power, a sample size (assumed the same for each sample). You may also modify α (type I error rate) and the power, if relevant. After making your entries, hit the **calculate** button at the bottom.

- Calculate Sample Size (for specified Power)
- Calculate Power (for specified Sample Size)

Enter a value for p1:	.385
Enter a value for p2:	.165

- 1 Sided Test
- 2 Sided Test

Enter a value for α (default is .05):	.01
Enter a value for desired power (default is .80):	.92
The sample size (for each sample separately) is:	126

Reference: The calculations are the customary ones based on the normal approximation to the binomial distribution. See for example Hypothesis Testing: Categorical Data - Estimation of Sample Size and Power for Comparing Two Binomial Proportions in Bernard Rosner's

Fundamentals of Biostatistics.

Rollin Brant.

Temp URL:

file:///Users/selimkhan/Desktop/Power:Sample%20Size%20Calculator%20UBC.webarchive

Original URL: https://www.stat.ubc.ca/~rollin/stats/ssize/b2.html

Appendix 5. Award radon action challenge campaign champion Pollution Probe-Health Canada

POLLUTION PROBE

June 20, 2016

Selim Khan
Ahmadiyya Muslim Community
2620 Market St.
Cumberland, ON K4C 1A3

Dear Selim,

Thank you for being a part of Pollution Probe's **Radon Action Challenge**. By increasing awareness and understanding of radon gas and its health impacts, your community has made a lasting contribution to improved environmental health in your community.

Enclosed is a small token of our appreciation for your community's invaluable contributions to the Radon Action Challenge.

The Radon Action Challenge was a part of Pollution Probe's **Healthy Communities Campaign** – a public engagement platform that supports workplaces and communities as they strive to improve their environmental health. To celebrate the efforts of Healthy Communities Campaign participants, including those who took part in the Radon Action Challenge, Pollution Probe showcased the campaign at the World's Largest Sandbox in Ottawa on June 8, 2016.

The annual event invites Parliamentarians, media personalities, not-for-profits and industry professionals to gather in a giant sandbox with local children where they took part in a sandcastle-building competition to raise awareness about the need for collaboration on children's health issues. To highlight the critical link between the environment and human health, including the effects of exposure to radon gas, the Healthy Communities Campaign formed a sandcastle-building team at this year's event – taking third prize in the competition!

Thank you for helping us bring to life this exciting first year of the Radon Action Challenge, an important part of the Healthy Communities Campaign. We hope you will continue to be a part of this important program!

Warmly,

The Healthy Communities Campaign Team

Appendix 6. Award Ottawa Sandbox Healthy Communities campaign on radon awareness

POLLUTION PROBE

HEALTHY COMMUNITIES


Healthy Communities Campaign participants collaborate to build a sandcastle at the World's Largest Sandbox (left), and are awarded third prize for their creation (right).


The Healthy Communities team add trees made from recycled paper to their sandcastle (left), and local families make the most of the sandbox (right).

Appendix 7. Abstract, 2nd Students' Conference in Population Health, University of Ottawa, 2016

uOttawa

2nd Student Conference in Population Health
Environment & Health

FSS4004 from 9:00 am to 6:00 pm
May 16th 2016 / 16 mai 2016
Université d'Ottawa – University of Ottawa

8- KHAN, Selim M.

Indoor Radon Mitigation Options for the Vulnerable Canadian Homes

Mots-clés / Keywords: Indoor air pollution, Economic Evaluation, Population Health

Résumé / Abstract:

People spend 90% of their time indoor; therefore, quality of indoor air is an important determinant of population health. About 7% of Canadian homes have Radon above the reference level (200Bq/m3) and it is higher than that in any of the G8 countries. Radon is a naturally occurring colorless, odorless, radioactive gas and is harmful when accumulates in a closed environment. Upon further decays, Radon releases radioactive alpha particles that potentially damage DNA of lung tissues. Radon represents 50% of all individual lifetime radiation exposures and is the second leading cause of lung cancer death after smoking in Canada. Radon kills an estimated 3,261 Canadians each year that is 16% of all lung cancer deaths. From population health perspective, children, women, and particularly smokers from lower socioeconomic group living in vulnerable old houses are disproportionately affected; they are losing school-, work-hours, and active years of life that has an annual economic burden of over $18 million. There is no updated economic evaluation of Radon mitigation measures in Canada; studies in the G8 countries show conflicting evidence around the cost-effectiveness of Radon mitigation options. As per Health Canada, if all homes were remediated up to the reference level, 927 of the anticipated deaths could potentially be prevented annually. But such universal program costs run into the millions of dollars. Thus, there is an obvious need for an economic evaluation to identify the most cost-effective mitigation option that can save lives of vulnerable population in Canada; thus; close the health equity gap.

Biographie / Biography: Selim M. Khan, MBBS (Dhaka), MPH (USA), Ph.D. in Population Health (student), Interdisciplinary School of Health Science, University of Ottawa. Working with Dr. James Gomes, MSc, Ph.D., Associate Professor, Environmental Health Research Unit, Interdisciplinary School of Health Sciences, University of Ottawa, ON, Canada.

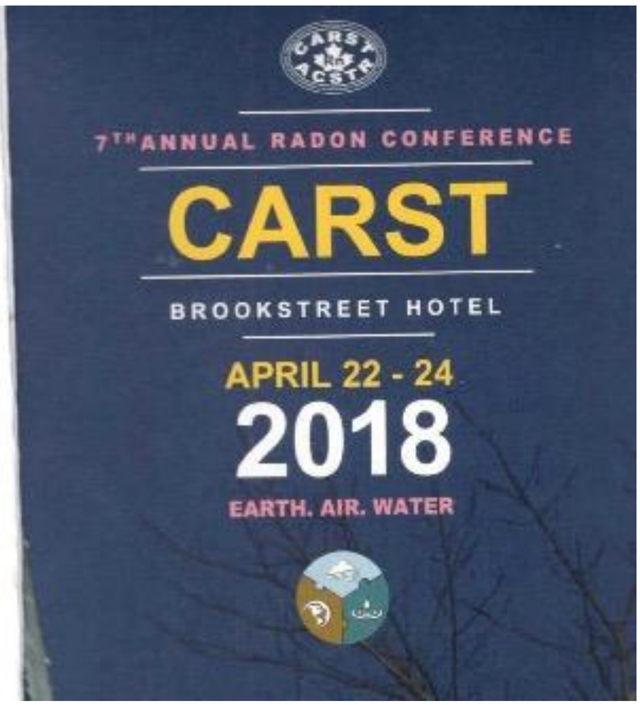
Appendix 8. Abstract presented in CARST annual conference 2018

Radon Health Risk Perception of Ottawa Residents

Dr. Selim Khan

Canadians have reason to care for indoor air quality as they spend over 90% of their time indoors. Due to the geographic location of Ottawa and because some of the houses are old, residents are at risk of high levels of radon exposure, particularly in the basements of older homes. Indoor radon causes more deaths than any other environmental hazard. Although 54% of residents are aware of the health risk of radon, only 5% have taken action.

The goal of this study was to understand residents' perceptions of the health risks of radon and to assess their perceived need to take action. An online survey was conducted with both homeowners and tenants in Ottawa and neighborhoods to quantify their perception of and adaptations for the risk. Although not a representative sample for the whole of Canada, this study reconfirmed previously tested hypotheses in a Canadian context. Low level of awareness and action show the inadequacy of government initiatives and ineffectiveness of risk communication messages. Concerted efforts by tapping into the identified perception points can produce better outcomes.



Appendix 9. Abstract presented in ISES/ISEE annual conference 2018

Wednesday, August 29
O03.01A. Carbon Monoxide and Radon in Residential Buildings
O03.01.01. A Mixed Methods Approach to Radon Health Risk Perception of Ottawa Residents

Selim Khan
Selim Khan1, James Gomes2, Samia Chreim3, Krewski Daniel4, Raywat Deonandan5
1. Interdisciplinary School of Health Sciences, University of Ottawa, Ottawa, ON, Canada.
2. Faculty of Health Sciences, University of Ottawa, Ottawa, ON, Canada.
3. Telfer School of Management, University of Ottawa, Ottawa, ON, Canada.
4. School of Epidemiology and Public Health, University of Ottawa, ON, Canada.
5. Faculty of Health Sciences, University of Ottawa, Ottawa, ON, Canada.

Abstract:

Background: Canadians have reason to care for indoor air quality as they spend over 90% of their time indoors. The geographic location and old houses make Ottawa residents at risk of the high level of radon exposure. Indoor radon causes more deaths than any other environmental hazards. While 55% residents are aware of the health risk, only 6% have taken action.

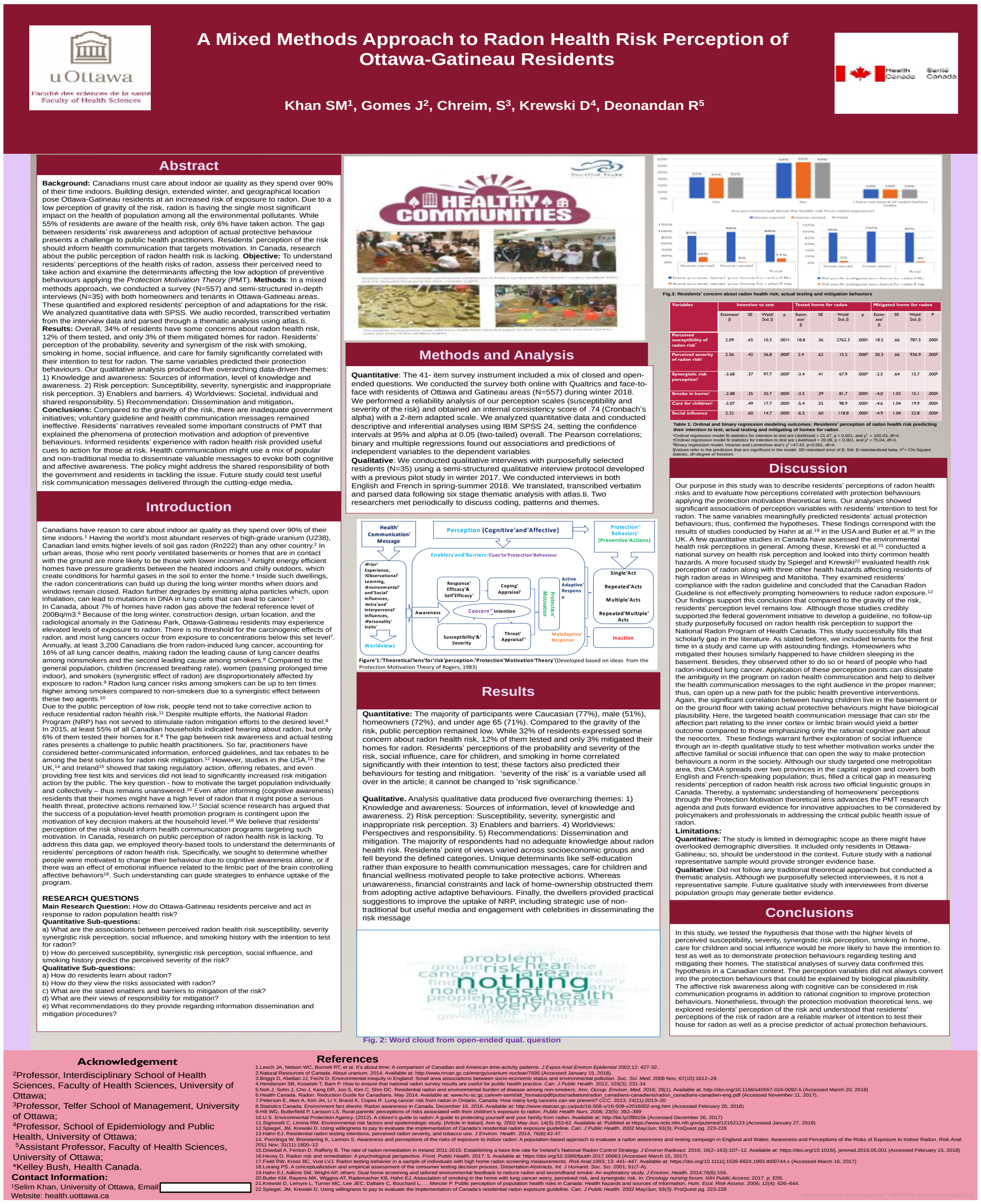
Objective: To understand residents' perceptions of the health risks of radon and to assess their perceived need to take action.

Methods: In mixed methods approach, an online survey (n=308) with Qualtrics and semi-structured face to face qualitative interviews (n=35) were conducted with both homeowners and tenants in Ottawa. These quantified and explored residents' perception of and adaptations for the risk. Quantitative data were analyzed in SPSS and qualitative analysis was done in Atlas-Ti using a two-coder iterative content approach.

Results: The majority of participants were Caucasian (77%), male (51%), homeowners (72%), and under age 65 (71%). Overall, 34% residents have some concerns about radon health risk, 12% have tested, and only 4% mitigated their homes for radon. Residents' perception of the severity of the risk, social influence, and smoking history significantly correlate with their intention to test for radon whereas synergistic risk perception with smoking predicts the perception of severity of the risk. Three themes emerged from qualitative analyses of interviews: 1) despite the gravity of radon health risks, there are minimum government programs to inform residents. 2) residents' concern about the risk and care for family welfare motivate them to take action. 3) health communication program should tap into the emotional aspect of awareness beyond the cognitive awareness.

Conclusions: There are inadequate government initiatives, and the health communication messages remained ineffective. Policy should address the shared responsibility of both government and residents in tackling the issue.

Appendix 10. Poster presented in the annual ISES/ISEE annual conference 2018



Appendix 11. Award for presentation in GSAED interdisciplinary conference 2018-2019

GSAÉD

GRADUATE STUDENTS ASSOCIATION
DES ÉTUDIANT.ES DIPLÔMÉ.ES DE
L'UNIVERSITÉ D'OTTAWA

CERTIFICATE OF APPRECIATION

This award is granted to

SELIM M. KHAN

For participating at the GSAÉD Interdisciplinary Conference (2018- 2019) as a speaker and for contributing to the development of knowledge in the academia.

Conference held on March 5th, 2019

Signed

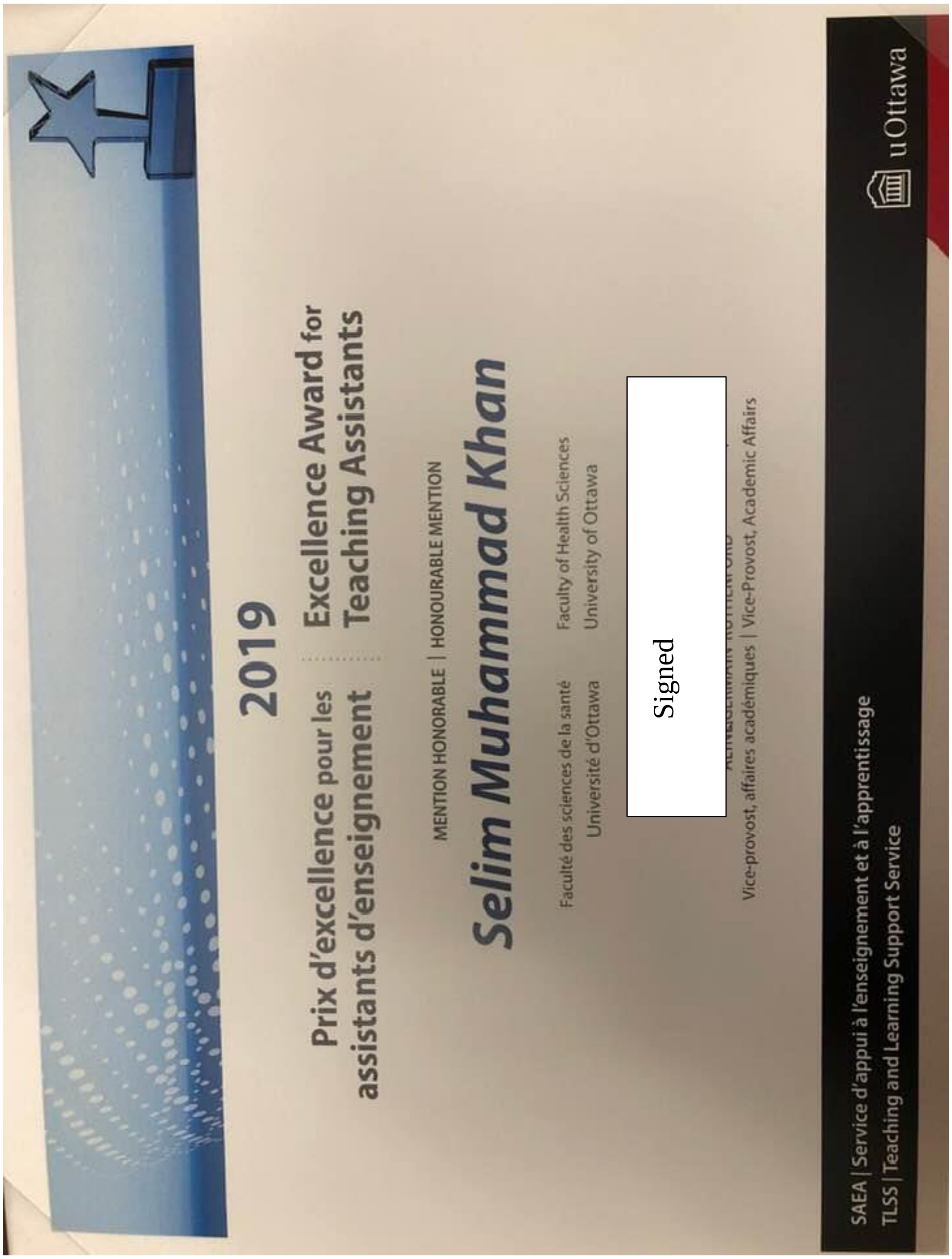
Khaled Kchouk
University Affairs Commissioner
GSAÉD
(Local 94 of the Canadian Federation of Students)
University of Ottawa

GSAÉD
U. d'Ottawa - U of Ottawa
601 Cumberland
Ottawa, ON K1N 6N5

Signed

Lucie Morin
Operations Coordinator
GSAÉD
(Local 94 of the Canadian Federation of Students)

Appendix 12. Excellence Award 2019 for Teaching Assistant



Appendix 13. Abstract accepted by the CARST Radon Conference 2019 in Saskatoon, SK.

Canadian Association of Radon Scientists and Technologists
Association Canadienne des Scientifiques et Technologues de Radon

April 8, 2019

Dear Mr. Selim Khan,

We would like to thank you for your submission to present a poster at this year's CARST Conference and let you know that your Poster has been accepted. We have provided a template that you can use if you don't already have it printed. Let us know if you would like us to print it for you and we can have it ready for you in Saskatoon.

https://www.makesigns.com/SciPosters_Templates.aspx We are asking people to choose the 48x36 (landscape) options.

We would like to display the posters at the Meet and Greet on Sunday evening, and then we will have a break as well that we would like to have you available to answer questions. We will let you know which break once we have confirmed the schedule.

Let us know if you need a hotel room and we can contact them for room rate or you can try and book here: Sheraton Cavalier Saskatoon hotel, 612 Spadina Crescent East, Saskatoon, SK, S7K 3G9

You can find all the conference details here: https://carst.ca/CARST-2019

Please let us know if you need any other information or assistance. We look forward to having you attend.

Sincerely,

Signed

Sandy, Colin, Jill, Jennifer, Frank, Pam and Erin
2019 Conference Committee

Helping Canadians reduce radon risk
Aider les Canadiens à réduire le risque du radon
www.carst.ca

Appendix 14. Poster Radon Conference 2019 in Saskatoon, SK, Canada

Residents' perceptions of radon health risks: a qualitative study

Residents' perceptions of radon health risks: a qualitative study

uOttawa
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Canada's university

Residents' Perception of Radon Health Risk: A Qualitative Study

Selim Khan[1] & Samia Chreim[2]

[1]Interdisciplinary School of Health Sciences, [2]Telfr School of Management, University of Ottawa

Health Canada Santé Canada

CARST Radon Conference, Saskatoon, SK, April 28-30, 2019

Abstract

Background: Radon is a high impact environmental pollutant and is the second leading cause of lung cancer in Canada. Building design, extended winter, and geographical location expose residents of Ottawa-Gatineau (the national capital region in Canada) to an increased risk. It is surprising that residents have an inadequate awareness of the risk - despite its gravity - and have taken minimum preventive actions. This study explores perceptions of radon health risk and examines the factors that enable and hinder the adoption of preventive measures among Ottawa-Gatineau residents.
Methods: We conducted semi-structured interviews with 35 residents from varying educational levels and occupational backgrounds to inquire about their knowledge and perception of radon, and to explore their views of enablers and obstacles to taking action to reduce radon risks. Thematic, inductive data analysis was undertaken.
Results: The results indicate that: 1) Residents obtained information on radon from various sources - the media, self-education or occupation, social network, and home renovation events. Limited references were made to the National Radon Program responsible for testing for radon and informing residents. 2) Awareness of radon risk varies, knowledge retained by some residents is insufficient to protect their health adequately. Residents who had dual perceptions- *cognitive as well as emotional awareness*, motivated enough to act. 3) Enablers for taking protective action: understanding the risk along with health consciousness; caring for family and children; knowing others who had contracted lung cancer and having financial resources. Obstacles included: lack of awareness; cost; lack of home ownership; and potential difficulty in selling the house. 4) Residents attributed primary responsibility to public agencies for disseminating information and incentivizing or mandating action through more stringent regulation.
Conclusion: Risk perceptions are subjective and influenced by the micro and macro level factors. Inducing protective action requires complex interventions considering dual perceptions of the threat by the public health agencies.

Introduction

Radon is a ubiquitous environmental pollutant that poses a significant health risk, especially in cold countries [1]. In Canada, radon kills at least 3,000 people annually, making it the second leading cause of lung cancer [2]. This naturally-emitted soil gas enters buildings, typically by seeping in through foundations [1]. Building design, extended winter, and geographical location expose residents to increased concentrations of radon gas [3, 4]. Radon decay gives off tiny radioactive particles that, when inhaled, can cause mutation in DNA of lung cells eventually resulting in lung cancer [5, 6]. Women and children appear to be more strongly affected [7], and the risk is up to threefold for smokers [8].
The National Radon Program (NRP) of Health Canada is responsible for raising public awareness through disseminating radon health risk messages [9]. Despite multiple efforts, the program lags behind the desired public uptake. According to the latest national survey, 55% of Canadian households heard about radon, but only 6% of them tested for it [2]. Similarly, a recent survey conducted in the national capital region in Canada, which is known for relatively elevated levels of radon, revealed that while 32% of those surveyed expressed some concern about radon health risks, only 12% tested for radon, and 3% took action to reduce radon health risks [10]. The gap between risk awareness and actual testing rates presents a challenge for public health professionals [11, 12].
In Canada, like many other countries, residents are responsible for radon testing and remediation [1, 9]. The guideline issued by the federal government is voluntary; it assumes that residents will act rationally according to the provided information [9]. This assumption, however, has been challenged by previous psychological and preventive health research relating to health risk perception [13, 14]. Further, Spiegel and Krewski [11], in a quantitative study, assessed the health risk perception of residents in high radon areas and concluded that the Canadian residential radon exposure guideline had not been effective at prompting homeowners to take action to reduce exposure.

Theoretical Lens: Protection Motivation Theory

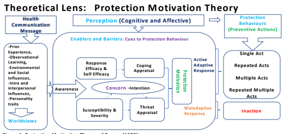

Figure 1. Protection Motivation Theory of Rogers (1983).

Thesis & Research Questions

The term 'risk' denotes the probability of experiencing a dangerous event times the magnitude of the consequences of that event [15]. However, studies over the decades have provided convincing evidence that subjective public perceptions of risk differ significantly from the scientific evaluation of risk [16, 17, 18]. For example, in a high seismic zone, the risk that a resident will die in an earthquake may be mathematically lower than the risk of dying in a car accident. Yet, residents are comfortable with driving but panicked of an earthquake [19]. This is because residents do not mathematically or objectively calculate the risk. Slovic argues that no risk exists independently of human thoughts and culture [20]. Attempts to reduce health risks would benefit from an understanding of people's views. Research has identified that the success of any population-level awareness program is contingent on the views and actions of key decision makers at the household level [21]. Therefore, it is important to understand residents' knowledge and views of radon health risk. Most studies that assess environmental health risk perceptions in Canada adopt quantitative approaches. To our knowledge, no qualitative study has been conducted that examines residents' knowledge and understanding of radon health risks, their views of enablers and obstacles to testing and mitigating, and their suggestions regarding how to improve the public's knowledge and action with respect to radon. Qualitative research enhances understanding of people's perceptions and experiences and is well suited to capture these views and their context in people's own words [22, 23]. It is important to achieve an understanding of residents' views. Therefore, this qualitative study applied the protection motivation theoretical lens and focused on three ***research questions***:

1) How do residents learn about radon and how do they view the risks associated with it?
2) What are the enablers and barriers to mitigation of the risk according to residents?
3) What suggestions do they provide to enhance information dissemination and protective action?

Methodology

This qualitative study follows a quantitative study we previously conducted with residents of the Ottawa-Gatineau area [10]. From that study, we purposefully selected 32 who had shown at least some background knowledge of radon. They were homeowners and tenants; individuals tested and not tested homes for radon; with various educational and occupational backgrounds. We included three interviews conveniently sampled for a pilot study on the same topic. In total, we conducted thirty-five interviews.

Table 1. Presents study participants' sociodemographic characteristics

Characteristics	Numbers	Percentage
Gender		
Female	8	23%
Male	27	77%
Age Groups		
18-44	7	20%
45-64	15	43%
65+	13	37%
Level of Education		
High School	3	9%
College	9	26%
Bachelor	11	31%
Graduate	12	34%
Total Household Income		
Less than $40,000	3	9%
Between $41,000-75,000	7	20%
Between $76,000-100,000	9	26%
Between $101,000-150,000	11	31%
Between $151,000 and Above	2	5%
Prefer Not to Answer	3	9%
Homeownership		
Homeowner	29	83%
Tenant	6	17%

Analysis

We adopted an inductive approach to the analysis and focused on understanding issues from the perspective of residents. Following Braun and Clarke [22] and Miles et al. [23], after familiarization with the transcripts, initial codes that were close to the data were applied. The first author initially coded seven interviews, using descriptive codes. The process of coding was iterative: as this coding progressed, new codes were added, and some codes were modified. Following this step, the second author reviewed the coded interviews, and the two researchers developed a code list [22] that was used to recode the interviews. The first author then continued coding the other transcripts, while also convening with the second author on a regular basis to discuss emerging patterns in the data. These patterns or themes were developed in answer to the research questions. For example, initial descriptive coding indicated that some participants had learned about radon from newspapers, radio, TV and/or the internet. Each of these four had its own code, and these codes were then combined under the theme of "media sources," which was one of the themes helping us to answer the research question on sources of information on radon. Our final themes and sub-themes are presented in ***Table 2***.

Results

In this section, we report the results of our analysis in four overarching themes and associated sub-theme. These are the 'sources of information' and 'level of knowledge or risk awareness' of participants. Followed by participants' views of enablers and obstacles to testing and mitigation. Finally, a summary of participants' suggestions regarding the ways to improve disseminating information and taking action to reduce radon harm.

Table 2. Themes and sub-themes obtained from qualitative data

	Themes	Sub-themes
1	**Source of knowledge**	Media Social network Education and occupation Home renovation shows Home inspectors The current study National Radon Program
2	**Knowledge-risk awareness**	Advanced Basic Deficient Faulty
3	**Enablers**	Understanding health risk (cognitive awareness) Concern for children and oneself (emotional awareness) Social influence (knowledge of significant others) Personalizing the risk Financial capability
	Barriers	Lack of awareness of health risk Cumbersome procedures Cost of remediation Tenancy Reduced property value (assumed) Voluntary nature of the guidelines
4	**Suggestions** to improve knowledge dissemination and protective action	Role of public agencies Individual responsibility Shared responsibility Role of citizenry Incentivizing Mandating and legislating

Fig 2. Word cloud of responses to question 'what else you know about radon?'

Conclusion

This study sheds light on the vital topic of residents' knowledge and views of radon and its risks. To date, studies on views of radon risk in Canada have tended to adopt quantitative approaches. The value of the qualitative approach is that it provides a deeper look into participants' experiences, thus providing information to complement quantitative results. Our study showed that many people do not get the crucial information on radon and some retain misconceptions about the health risks of radon even after being exposed to information. Many residents report barriers in testing and engaging in protective action, even after receiving the pertinent information.
Our study underscores the importance of seriously considering how radon risk is understood and dealt with by residents. We identified that mere cognitive risk awareness is not enough; additional emotional awareness motivates residents to take action regarding testing and mitigating their houses for radon. Therefore, radon health communication will be more effective when programs address both these aspects of risk perception along with plausible regulations and incentives, where necessary. Future research can explore the dual aspects of risk perception and thus help to develop tailored risk communication messages capable of motivating residents to mitigate their homes for radon health risk.

Limitations and Future Research Direction

A limitation of this study is our inability to generalize from the current study to the population at large; however, this is a typical feature of qualitative studies [23]. In fact, exploratory qualitative studies are not intended to provide generalizable data, but to enhance understandings that can be further tested in broader-based quantitative studies. Our study was also limited in number of participants and locations.
Future research would benefit from interviewing more participants and in other cities to generate additional insights. We believe that studies in cities where there have been condensed and concerted efforts to communicate with residents and incentivize action would provide an interesting extension of or counterpoint to this study.

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Acknowledgements

Grateful to all our study participants.
Supervisors: Dr. James Gomes, Dr. Samia Chreim
Thesis advising committee: Dr. Daniel Krewski, Dr. Raywat Deonandan
Funding: McLaughlin Centre for Population Health Risk Assessment
University of Ottawa, Ontario Graduate Scholarship
Support in Kind: Health Canada.

Appendix 15. Abstract accepted for the RAPID Workshop 2019 in Calgary, Alberta.

A Population Health Approach to the Radon Health Risk: Perception of Ottawa-Gatineau Residents

Selim Khan1, James Gomes2, Samia Chreim3, Krewski Daniel4, Raywat Deonandan5
1. Interdisciplinary School of Health Sciences, University of Ottawa, Ottawa, ON, Canada.
2. Faculty of Health Sciences, University of Ottawa, Ottawa, ON, Canada.
3. Telfer School of Management, University of Ottawa, Ottawa, ON, Canada.
4. School of Epidemiology and Public Health, University of Ottawa, ON, Canada.
5. Faculty of Health Sciences, University of Ottawa, Ottawa, ON, Canada.

Abstract

Background: Canadians have reason to care for indoor air quality as they spend over 90% of their time indoors. Building design, extended winter, and geographical location expose residents of Ottawa-Gatineau (the national capital region in Canada) to an increased risk. Indoor radon causes more deaths than any other environmental hazards. While 55% of residents have heard about radon, only 6% have taken action. The gap between residents' risk awareness and the adoption of actual protective behaviour presents a challenge to public health practitioners. Research indicates that residents' perception of the risk should inform health communication that targets motivation for action. In Canada, research about the public perception of radon health risk is lacking.

Objective: To explore resident's perceptions of radon health risk and examine the factors that enable and hinder the adoption of preventive measures among Ottawa-Gatineau residents.

Methods: In a mixed methods approach, a complex survey (N=557) and qualitative interviews (N=35) were conducted with both homeowners and tenants in Ottawa-Gatineau areas. These quantified and explored residents' perception of and adaptations for the risk. We analyzed quantitative data in SPSS and qualitative analysis in Atlas-Ti using a two-coder iterative content approach.

Results: Overall, 34% of residents have some concerns about radon health risk, 12% have tested, and only 3% mitigated their homes for radon. Residents' perception of the probability, severity and synergism of the risk with smoking, smoking in the home, social influence, and care for family significantly correlated with their intention to test for radon; the same variable predicted their protection behaviours. Qualitative analysis indicated that a) Residents obtained information on radon from the media, their education or occupation, social network, and home renovation events. b). Residents who had dual perceptions- cognitive as well as emotional awareness, were motivated enough to take action. c) Enablers for taking protective action included: having an understanding of the risk along with health consciousness; caring for family and children; knowing others who had contracted lung cancer and having financial resources. Obstacles consisted lack of awareness, cost of mitigation, lack of home ownership and potential difficulty in selling the house. d) Residents attributed primary responsibility to public agencies for disseminating information, and incentivizing or mandating action through more stringent regulation.

Appendix 16. Informed consent form for qualitative interview (English)

uOttawa
Faculté des sciences de la santé
Faculty of Health Sciences

Université d'Ottawa

Faculté des sciences de la santé
École interdisciplinaire en sciences de la sante

University of Ottawa

Faculty of Health Sciences
Interdisciplinary School in Health Sciences

Informed Consent Form: (Qualitative Interview)

Title of the Study: A Population Health Approach to Examine Ottawa-Gatineau Residents' Perception of Radon Health Risk

Names and Affiliations of Researchers:

Principal Investigator: Selim M. Khan
PhD Population Health Candidate
Interdisciplinary School of Health Sciences
210 Thompson, 25 University Private
University of Ottawa, Ottawa, ON, K1N7K4
Email: xxx
Cell: xxx

Supervisor: Dr. James Gomes, Associate Professor
Interdisciplinary School of Health Sciences
210 Thompson, 25 University Private
University of Ottawa, Ottawa, ON, K1N7K4
Email: xxx
Office: xxx

Co-Supervisor: Dr. Samia Chreim, Professor
Telfer School of Management,
55 Laurier Ave East
University of Ottawa, Ottawa, ON, K1N65
Email: xxx
Office: xxx

Invitation to Participate: I am invited to participate in this study on indoor air quality, specifically radon, conducted by Selim Khan for his doctoral thesis. I am informed that radon is a colorless, odorless, radioactive gas coming from soil and seeps into the houses through basement. Once inhaled, it can cause lung cancer in the long-term. Children, and women are at increased risk.

Tel: 613 562 5800
Fax: 613 562 5632
25 University Ptv.
Ottawa, ON, K1N 6N5
Canada

Purpose and Goal of the Study: I realize that the purpose of the study is to gain an in-depth understanding of residents' perception of indoor radon public health risk. The study goal is to prevent radon-induced lung cancer morbidity and mortality in Canada.

Description of participation: My participation will consist of taking part once in an individual interview lasting about 40-60 minutes. During which I will answer a list of open- and close-ended questions, provide my opinions and comments. The interview will be scheduled at my convenient place, preferably in my house, on a date and time that is suitable for me. I give consent to record the interview session for better data collection purpose: Yes [ ], No [ ] and to quote me anonymously where necessary in the literature: Yes [ ], No[ ].. I also agree with taking the observation notes during the interview: Yes [ ], No[ ]. I allow inspection of and taking photographs of the radon plant installed in my house: Yes [ ], No[ ].

Rights of the Research Participant: I understand that my participation in this study is voluntary and I am under no obligation. I will have the right to refuse to answer any question without fear of reprisal. I understand that since my participation in this study will entail voluntarily sharing some information related to my house, though not intimately personal, these may still cause me to feel inconveniences (emotionally or psychologically) in case of someone from my household or relatives has/had a lung cancer. I am receiving assurance from the researcher that every effort will be made to minimize these risks. It is made clear to me that at any point during the interview if I feel discomfort or stress, I can stop answering any question or completely withdraw from the study. In that case, the interview will be terminated and the information collected till that time will be deleted immediately. For further support, I can contact a psychosocial counselor at Ottawa Public Health's helpline (613-722-6914) that is accessible free of cost 24/7.

Benefits: My participation in this study will enhance my understanding of the population health risk of radon, and this will benefit me to update my knowledge about the risk. I will know more about the available risk management options and their effectiveness. I will have a chance to talk about the importance of indoor air quality and the probability of lung cancer from indoor radon. Besides, getting a test kit will allow me to know the radon level in my house, and if high, I can decide independently to mitigate it; thus, I can reduce the risk to get radon-induced lung cancer.

Confidentiality and anonymity: I have received assurance from the researcher that the information I share will remain strictly confidential. The contents will be used only for the research purpose. There is no risk of breach of confidentiality because of any legal obligation. Anonymity will be protected by removing my name, address, and all identifiable information from the written reports. However, for the presentation purpose, pseudonyms and codes can be used.

Information about the Study Results: We agree herewith the research findings will be made available to me sending in a password protected file attached with an email.

Conservation of data: The data collected (digital recording of interview and interview transcript) will be encrypted and stored on a password protected computer. Physical data (observation notes) will be locked in a secured safe. Only the above-listed investigators will have access to these data. The data will be conserved for five years as per the Ethics Review Board's requirement.

Compensation: There is no monetary compensation, but a radon test kit (price including return envelope from the lab and lab fee about $45) will be provided to me, if I agree to get one, as a token for the time taken.

Acceptance:

I, ____________________________, agree to participate in the above research study conducted by Selim Khan of the University of Ottawa, supervised by Dr. James Gomes and Dr. Samia Chreim. I understand that by accepting to participate, I am in no way waiving my right to withdraw from the study. If I have any questions about the study, I may contact the student and/or supervisors at the numbers mentioned above.

The McLaughlin Centre for Population Health Risk Assessment is supporting this study by providing radon test kits. The investigator declares that there is no conflict of interest as to sell or solicit anything or neither there is any other vested issue.

If I have any ethical concerns regarding my participation in this study, I may contact the Protocol Officer for Ethics in Research, University of Ottawa, 550 Cumberland Street, Room 154, (613) 562-5387 or ethics@uottawa.ca.

There are two copies of the consent form, one of which is mine to keep.

Participant's signature: __________________________ Date: ______________________

Researcher's signature: __________________________ Date: _______________________

Appendix 17. Informed consent form for qualitative interview (French)

uOttawa

Faculté des sciences de la santé
Faculty of Health Sciences

Université d'Ottawa

Faculté des sciences de la santé
École interdisciplinaire en sciences de la sante

University of Ottawa

Faculty of Health Sciences
Interdisciplinary School in Health Sciences

Formulaire de consentement éclairé : (Entretien Qualitatif)

Le titre de l'étude : Une approche axée sur la santé de la population pour examiner la perception du risque de radon par les résidents d'Ottawa-Gatineau

Names and Institutional Affiliation of the Researchers:

Chercheur principal : Selim Khan
Candidat au doctorat en santé de la population
École interdisciplinaire des sciences de la santé
210 Thompson, 25 Université privée
Ottawa, ON, K1N7K4
Université d'Ottawa,
Courriel : xxx
Tél. cellulaire : … …. …..

Superviseur : Dr. James Gomes , Professeur Agrégé
École interdisciplinaire des sciences de la santé
210 Thompson, 25 Université privée
Université d'Ottawa, Ottawa, ON, K1N7K4
Courriel : xxx
Tél. Bureau : xxx

Co-superviseur : Dr. Samia Chreim, Professeur
École de gestion Telfer
55, avenue Laurier Est
Université d'Ottawa,
Ottawa, ON, K1N65
Courriel : xxx
Tél. Bureau : xxx

Invitation à participer :
Je suis invité à participer à cette étude sur la qualité de l'air intérieur, en particulier l e radon, menée par Selim Khan pour sa thèse de doctorat. On m'informe que le radon est un gaz radioactif incolore et

inodore qui provient du sol et s'infiltre dans les maisons par le sous-sol. Une fois inhalé, il peut causer le cancer du poumon à long terme. Les enfants et les femmes sont exposés à un risque accru.

Objectif et but de l'étude : Je réalise que le but de l'étude est d'acquérir une compréhension approfondie de la perception qu'ont les résidents des risques pour la santé publique liés au radon à l'intérieur. L'objectif de l'étude est de prévenir la morbidité et la mortalité par cancer du poumon induit par le radon au Canada.

Description de la participation : Ma participation consistera à participer une fois à une entrevue individuelle d'environ 40-60 minutes. Au cours de laquelle je vais répondre à une liste de questions ouvertes et fermées, fournir mes opinions et commentaires. L'interview sera programmée à mon endroit approprié, de préférence chez moi, à une date et une heure qui me conviennent. Je consens à enregistrer la session d'interview pour un meilleur but de collecte de données : Oui [], Non [] et me citer anonymement si nécessaire dans la littérature : Oui [ ], Non [ ] . Je suis également d'accord avec les notes d'observation l'interview : Oui [ ], Non [ ]. J'autorise l'inspection et la prise de photographies de l'usine de radon installée chez moi : Oui [ ], Non [ ].

Droits du participant à la recherche : Je comprends que ma participation à cette étude est volontaire et je n'ai aucune obligation. J'aurai le droit de refuser de répondre à toute question sans crainte de représailles. Je comprends que puisque ma participation à cette étude impliquera volontairement le partage de certaines informations relatives à ma maison, même si elles ne sont pas intimement personnelles, elles peuvent encore me causer des désagréments (émotionnels ou psychologiques) au cas où quelqu'un de ma famille ou de ma famille un cancer du poumon. Je reçois l'assurance du chercheur que tous les efforts seront faits pour minimiser ces risques. Il est clair pour moi qu'à tout moment de l'entrevue, si je ressens de l'inconfort ou du stress, je peux arrêter de répondre à toute question ou me retirer complètement de l'étude. Dans ce cas, l'interview sera terminée et les informations recueillies jusqu'à ce moment seront immédiatement effacées. Pour obtenir de l'aide supplémentaire, je peux communiquer avec un conseiller psychosocial à la ligne d'aide d'Ottawa Public Health (613-722-6914), accessible gratuitement 24 heures par jour, 7 jours par semaine.

Avantages : Ma participation à cette étude améliorera ma compréhension du risque pour la santé de la population liée au radon, ce qui me permettra de mettre à jour mes connaissances sur le risque. J'en saurai plus sur les options de gestion des risques disponibles et leur efficacité. J'aurai l'occasion de parler de l'importance de la qualité de l'air intérieur et de la probabilité de développer un cancer du poumon à l'intérieur du radon. De plus, l'obtention d'un kit de test me permettra de connaître le niveau de radon dans ma maison, et s'il est élevé, je pourrai décider de l'atténuer de manière indépendante ; Ainsi, je peux réduire le risque d'avoir un cancer du poumon induit par le radon.

Confidentialité et anonymat : J'ai reçu l'assurance du chercheur que les informations que je partage resteront strictement confidentielles. Le contenu sera utilisé uniquement à des fins de recherche. Il n'y a aucun risque de violation de la confidentialité en raison d'une obligation légale. L'anonymat sera protégé en supprimant mon nom, mon adresse et toutes les informations identifiables des rapports écrits. Cependant, à des fins de présentation, des pseudonymes et des codes peuvent être utilisés.

Informations sur les résultats de l'étude : Nous sommes d'accord avec les résultats de la recherche qui seront mis à ma disposition en envoyant un fichier protégé par mot de passe joint à un courriel.

Conservation des données : Les données collectées (enregistrement numérique de l'interview et transcription de l'interview) seront cryptées et stockées sur un ordinateur protégé par mot de passe. Les données physiques (notes d'observation) seront verrouillées dans un coffre sécurisé.

Seuls les investigateurs listés ci-dessus auront accès à ces données. Les données seront conservées pendant cinq ans conformément aux exigences du Conseil d'éthique

Compensation : Il n'y a pas de compensation monétaire, mais une trousse d'analyse du radon (prix incluant l'enveloppe de retour du laboratoire et frais de laboratoire d'environ 45 $) me sera fournie, si j'accepte d'en obtenir un, pour le temps nécessaire.

Acceptation :

Je, ____________________________, accepte de participer à l'étude de recherche ci-dessus menée par Selim Khan de l'Université d'Ottawa, supervisée par le Dr James Gomes et le Dr Samia Chreim. Je comprends qu'en acceptant de participer, je ne renonce en aucun cas à mon droit de me retirer de l'étude. Si j'ai des questions sur l'étude, je peux contacter l'étudiant et / ou les superviseurs aux numéros mentionnés ci-dessus.

Le Centre McLaughlin d'évaluation des risques pour la santé des populations appuie cette étude en fournissant des trousses d'analyse du radon. L'enquêteur déclare qu'il n'y a pas de conflit d'intérêts quant à la vente ou la sollicitation de quelque chose ou qu'il n'y a pas d'autre problème.

Si j'ai des préoccupations d'ordre éthique concernant ma participation à cette étude, je peux communiquer avec l'agent de protocole pour l'éthique de la recherche, Université d'Ottawa, 550, rue Cumberland, bureau 154, (613) 562-5387 ou ethics@uottawa.ca.

Il y a deux copies du formulaire de consentement, dont l'une est à moi.

Signature du participant : __________________________ Date : ______________________

Signature du chercheur : __________________________ Date : ______________________

Appendix 18. Implied Consent for online survey (English)

Université d'Ottawa

Faculté des sciences de la santé
École interdisciplinaire en sciences de la sante

University of Ottawa

Faculty of Health Sciences
Interdisciplinary School in Health Sciences

Title of the study: A Population Health Approach to Examine Ottawa-Gatineau Resident's Perception of Radon Health Risk

Names and Institutional Affiliation of the Researchers:

Principal Investigator: Selim M. Khan, PhD Population Health Candidate
Interdisciplinary School of Health Sciences
210 Thompson, 25 University Private
University of Ottawa, Ottawa, ON, K1N7K4
Email: xxx
Cell: xxx

Supervisor: Dr. James Gomes, Associate Professor
Interdisciplinary School of Health Sciences
210 Thompson, 25 University Private
University of Ottawa, Ottawa, ON, K1N7K4
Email: xxx
Office: xxx

Co-Supervisor: Dr. Samia Chreim, Professor
Telfer School of Management
55 Laurier Ave East
University of Ottawa, Ottawa, ON, K1N65
Email: xxx
Office: xxx

Invitation to Participate:

I am invited to participate in this study related to indoor air quality, specifically radon conducted by Selim Khan for his doctoral thesis. I am informed that radon is a colorless, odorless, radioactive gas coming from soil and seeps into the houses through the basement. Once inhaled, it can cause lung cancer in the long-term. Children and women are at increased risk, and the risk is threefold for the smokers.

Purpose and Goal of the Study: I understand that the purpose of this study is to know citizen's perception of radon health risk and suitable adaptation technique. The information collected will help to identify why radon testing and mitigation rates remained low; thus, to find out evidence to inform the policy decisions.

Description of Participation: My participation in this study includes taking a survey either online or physically that may take about 30 minutes to complete. My decision to complete and return this survey will be interpreted as an indication of my consent to participate. I understand that I do not have to answer any question that I do not want to. Once completed online, I will log out and shout the survey to protect my privacy. Once filled in physical copies, I will return it with the stamped self-addressed envelope as provided.

Note: I will endeavor to fill the survey within the set timeline. If I cannot, I will expect to receive a reminder from the researcher.

Rights of the Research Participant: I understand that my participation in this study is voluntary and I am under no obligation. I will have the right to refuse to answer any question without fear of reprisal. I understand that since my participation in this study will entail voluntarily sharing some information related to my house, though not intimately personal, these may still cause me to feel inconveniences (emotionally or psychologically) in case of someone from the household or relatives has/had a lung cancer. I am receiving assurance from the researcher that every effort will be made to minimize these risks. It is made clear to me that at any point during the interview if I feel discomfort or stress, I can stop answering any question or completely withdraw from the study. In that case, the interview will be terminated, and the information collected till that time will be deleted immediately. For further support, I can contact a psychosocial counselor at Ottawa Public Health's helpline (613-722-6914) that is accessible free of cost 24/7.

Benefits: My participation in this study will enhance my understanding of the population health risk of radon, and this will benefit me to update my knowledge about the risk. I will know more about the available risk management options and their effectiveness. I will have a chance to talk about the importance of indoor air quality and the probability of lung cancer from indoor radon. Besides, getting a test kit will allow me to know the radon level in my house, and if high, I can decide independently to mitigate it; thus, I can reduce the risk to get radon-induced lung cancer.

Confidentiality and Anonymity: The information that I will share will remain strictly confidential and will be used solely for this research. The only people who will have access to the research data are the principal researcher and his supervisors. The answers to the open-ended questions may be used verbatim in presentations and publications by anonymizing the identities with pseudonyms and codes. If filling the survey online, I am recommended to sign out and close the browser once done with the survey. These are to minimize the risk of security breaches and to ensure my confidentiality. The study results will be published in pooled (aggregate) format ensuring anonymity by replacing the personally identifiable information with pseudonyms and codes.

In order to minimize the risk of security breaches and to help ensure my confidentiality the researchers recommend that I use standard safety measures such as signing out of my account, closing my browser and locking my screen or device when I am no longer using them / when I have completed the study.

Conservation of data: The surveys data will be stored in a locked safe in the office of principal investigator at the University of Ottawa. On his leaving the university, the supervisor (professor) or his replacement will similarly keep the records stored safe for five years at which time these will be securely destroyed.

Voluntary Participation: I understand that I am under no obligation to participate, and if I choose to participate, I may refuse to answer any question that you do not want to. At any point in time I may withdraw from the survey; then, the information given will be deleted immediately. The completion and return of the questionnaire will imply my consent.

Information about the Study Results: We agree herewith the research findings will be made available to me sending in a password protected file attached with an email.

If you have any questions or require more information about the study itself, you may contact the researcher or his supervisors at the numbers mentioned herein.

The McLaughlin Centre for Population Health Risk Assessment is supporting this study by providing radon test kits. The investigator declares that there is no conflict of interest as to sell or solicit anything or neither there is any other vested issue.

If you have any questions with regards to the ethical conduct of this study, you may contact the Protocol Officer for Ethics in Research, University of Ottawa, Tabaret Hall, 550 Cumberland Street, Room 154, Ottawa, ON K1N 6N5, tel.: (613) 562-5387 or ethics@uottawa.ca.

Please print out and keep a copy of this consent form for your records.

Thank you for your time and consideration.

Selim Khan,
November 16, 2017

Appendix 19. Implied Consent for online survey (French)

Consentement implicite : Sondage sur la perception des risques pour la santé du radon

Le titre de l'étude : Une approche axée sur la santé de la population pour examiner la perception du risque de radon par les résidents d'Ottawa-Gatineau

uOttawa

Faculté des sciences de la santé
Faculty of Health Sciences

Université d'Ottawa

Faculté des sciences de la santé
École interdisciplinaire en sciences de la sante

University of Ottawa

Faculty of Health Sciences
Interdisciplinary School in Health Sciences

Names and Institutional Affiliation of the Researchers:

Chercheur principal : Selim M. Khan
Candidat au doctorat en santé de la population
École interdisciplinaire des sciences de la santé
210 Thompson, 25 Université privée
Ottawa, ON, K1N7K4
Université d'Ottawa,
Courriel : xxx
Tél. cellulaire : xxx

Superviseur : Dr. James Gomes
Professeur Agrégé
École interdisciplinaire des sciences de la santé
210 Thompson, 25 Université privée
Université d'Ottawa, Ottawa, ON, K1N7K4
Courriel : xxx
Tél. Bureau : xxx

Co-superviseur: Dr. Samia Chreim
Professeur
École de gestion Telfer
55, avenue Laurier Est
Université d'Ottawa, Ottawa, ON, K1N65
Courriel : xxx
Tél. Bureau : xxx

Invitation à participer :

Je suis invité à participer à cette étude relative à la qualité de l'air intérieur, plus précisément au radon mené par Selim Khan pour sa thèse de doctorat. On m'informe que le radon est un gaz radioactif incolore et inodore provenant du sol et s'infiltrant dans les maisons par le sous-sol. Une fois inhalé, il peut causer le cancer du poumon à long terme. Les enfants et les femmes sont exposés à un risque accru, et le risque est triple pour les fumeurs.

de l'étude : Je comprends que le but de cette étude est de connaître la perception

Tel: 613 562 5800
Fax: 613 562 5632
25 University Ptv.
Ottawa, ON, K1N 6N5
Canada

www.uOttawa.ca

du citoyen quant au risque pour la santé du radon et à la technique d'adaptation appropriée. L'information recueillie aidera à déterminer pourquoi les taux de dépistage et d'atténuation du radon sont demeurés faibles ; ainsi, pour trouver des preuves pour informer les décisions politiques.

Description de la participation :

Ma participation à cette étude comprend un sondage en ligne ou physique qui peut prendre environ 30 minutes. Ma décision de remplir et de renvoyer ce sondage sera interprété comme une indication de mon consentement à participer. Je comprends que je n'ai pas à répondre à une question que je ne veux pas. Une fois terminé en ligne, je vais me déconnecter et crier le sondage pour protéger ma vie privée. Une fois rempli les copies physiques, je le retournerai avec l'enveloppe préaffranchie timbrée comme prévu.

Remarque : Je m'efforcerai de remplir le sondage dans les délais impartis. Si je ne peux pas, je m'attends à recevoir un rappel du chercheur.

Droits du participant à la recherche : Je comprends que ma participation à cette étude est volontaire et je n'ai aucune obligation. J'aurai le droit de refuser de répondre à toute question sans crainte de représailles. Je comprends que puisque ma participation à cette étude impliquera volontairement le partage de certaines informations relatives à ma maison, même si elles ne sont pas intimement personnelles, elles peuvent encore me causer des désagréments (émotionnels ou psychologiques) au cas où quelqu'un du ménage ou de la famille un cancer du poumon. Je reçois l'assurance du chercheur que tous les efforts seront faits pour minimiser ces risques. Il est clair pour moi qu'à tout moment de l'entrevue, si je ressens de l'inconfort ou du stress, je peux arrêter de répondre à toute question ou me retirer complètement de l'étude. Dans ce cas, l'interview sera terminée et les informations recueillies jusqu'à ce moment seront immédiatement effacées. Pour obtenir de l'aide supplémentaire, je peux communiquer avec un conseiller psychosocial à la ligne d'aide d'Ottawa Public Health (613-722-6914), accessible gratuitement 24 heures par jour, 7 jours par semaine.

Avantage : Ma participation à cette étude améliorera ma compréhension du risque pour la santé de la population liée au radon, ce qui me permettra de mettre à jour mes connaissances sur le risque. J'en saurai plus sur les options de gestion des risques disponibles et leur efficacité. J'aurai l'occasion de parler de l'importance de la qualité de l'air intérieur et de la probabilité de développer un cancer du poumon à l'intérieur du radon. De plus, l'obtention d'un kit de test me permettra de connaître le niveau de radon dans ma maison, et s'il est élevé, je pourrai décider de l'atténuer de manière indépendante ; Ainsi, je peux réduire le risque d'avoir un cancer du poumon induit par le radon.

Confidentialité et anonymat : Les informations que je partagerai resteront strictement confidentielles et seront utilisées uniquement pour cette recherche. Les seules personnes qui auront accès aux données de recherche sont le chercheur principal et ses superviseurs. Les réponses aux questions ouvertes peuvent être utilisées textuellement dans les présentations et les publications en anonymisation les identités avec des pseudonymes et des codes. Si vous remplissez le sondage en ligne, je vous recommande de vous déconnecter et de fermer le navigateur une fois le sondage terminé. Il s'agit de minimiser le risque d'atteinte à la sécurité et d'assurer ma confidentialité. Les résultats de l'étude seront publiés dans un format agrégé garantissant l'anonymat en remplaçant les informations personnellement identifiables par des pseudonymes et des codes.

Afin de minimiser le risque d'atteinte à la sécurité et d'assurer ma confidentialité, les chercheurs recommandent que j'utilise des mesures de sécurité standard telles que la fermeture de mon compte, la fermeture de mon navigateur et le verrouillage de mon écran ou de mon appareil lorsque je ne les utilise plus J'ai terminé l'étude.

Conservation des données : Les données des enquêtes seront conservées dans un coffre-fort verrouillé au bureau du chercheur principal de l'Université d'Ottawa. À sa sortie de l'université, le superviseur (professeur) ou son remplaçant conservera de la même façon les dossiers conservés en lieu sûr pendant cinq ans, après quoi ceux-ci seront détruits en toute sécurité.

Participation volontaire : Je comprends que je n'ai aucune obligation de participer, et si je choisis de participer, je peux refuser de répondre à toute question que vous ne voulez pas. À tout moment, je peux me retirer de l'enquête ; alors, l'information donnée sera effacée immédiatement. L'achèvement et le retour du questionnaire impliqueront mon consentement.

Informations sur les résultats de l'étude :

Nous sommes d'accord avec les résultats de la recherche qui seront mis à ma disposition en envoyant un fichier protégé par mot de passe joint à un courriel.

Si vous avez des questions ou avez besoin de plus d'informations sur l'étude elle-même, vous pouvez contacter le chercheur ou ses superviseurs aux numéros mentionnés ici.

Le Centre McLaughlin d'évaluation des risques pour la santé des populations appuie cette étude en fournissant des trousses d'analyse du radon. L'enquêteur déclare qu'il n'y a pas de conflit d'intérêts quant à la vente ou la sollicitation de quelque chose ou qu'il n'y a pas d'autre problème.

Si vous avez des questions concernant la conduite éthique de cette étude, vous pouvez contacter l'agente de protocole pour l'éthique en recherche, Université d'Ottawa, Pavillon Tabaret, 550, rue Cumberland, pièce 154, Ottawa, ON K1N 6N5, tél. 613) 562-5387 ou ethics@uottawa.ca.

Veuillez imprimer et conserver une copie de ce formulaire de consentement pour vos dossiers.

Merci pour votre temps et votre considération.

Selim Khan,
1er décembre 2017

Appendix 20. Informed consent for paper-based survey (English)

uOttawa

Faculté des sciences de la santé
Faculty of Health Sciences

Université d'Ottawa

Faculté des sciences de la santé
École interdisciplinaire en sciences de la sante

University of Ottawa

Faculty of Health Sciences
Interdisciplinary School in Health Sciences

Consent: Radon Health Risk Perception Survey (Paper-Based)

Title of the study: A Population Health Approach to Examine Ottawa-Gatineau Residents' Perception of Radon Health Risk

Names and Institutional Affiliation of the Researchers:

Principal Investigator: Selim M. Khan
PhD Population Health Candidate
Interdisciplinary School of Health Sciences
210 Thompson, 25 University Private
University of Ottawa, Ottawa, ON, K1N7K4
Email: xxx
Cell: xxx

Supervisor: Dr. James Gomes , Associate Professor
Interdisciplinary School of Health Sciences
210 Thompson, 25 University Private
University of Ottawa, Ottawa, ON, K1N7K4
Email : xxx
Email: xxx
Office: xxx

Co-Supervisor: Dr. Samia Chreim, Professor
Telfer School of Management
55 Laurier Ave East
University of Ottawa, Ottawa, ON, K1N65
Email: xxx
Office: xxx

Invitation to Participate: I am invited to participate in this study related to indoor air quality, specifically radon conducted by Selim Khan for his doctoral thesis. I am informed that radon is a colorless, odorless, radioactive gas coming from soil and seeps into the houses through the basement. Once inhaled, it can cause lung cancer in the long-term. Children and women are at increased risk, and the risk is threefold for the smokers.

Tel: 613 562 5800
Fax: 613 562 5632
25 University Ptv.
Ottawa, ON, K1N 6N5
Canada

www.uOttawa.ca

Purpose and Goal of the Study: I understand that the purpose of this study is to know citizen's perception of radon health risk and about the suitable adaptation technique. The information collected will help to identify why radon testing and mitigation rates remained low; thus, to find out evidence to inform the policy decisions.

Description of Participation: My participation in this study includes taking a paper-based survey that may take about 30 minutes to complete. My signature below is an indication of my consent to participate in this survey. I understand that I do not have to answer any question that I do not want to. Once filled the physical copies of the survey, I will hand it over to the researcher who ensured me of the strict confidentially of all my personally identifiable information.

Rights of the Research Participant: I understand that my participation in this study is voluntary and I am under no obligation. I will have the right to refuse to answer any question without fear of reprisal. I understand that since my participation in this study will entail voluntarily sharing of some information related to my house, though not intimately personal, these may still cause me to feel inconveniences (emotionally or psychologically) in case of someone from the household or relatives has/had a lung cancer. I am receiving assurance from the researcher that every effort will be made to minimize these risks. It is made clear to me that at any point during the interview if I feel discomfort or stress, I can stop answering any question or completely withdraw from the study. In that case, the interview will be terminated, and the information collected till that time will be deleted immediately. For further support, I can contact a psychosocial counselor at Ottawa Public Health's helpline (613-722-6914) that is accessible free of cost 24/7.

Benefits: My participation in this study will enhance my understanding of the population health risk of radon, and this will benefit me to update my knowledge about the risk. I will know more about the available risk management options and their effectiveness. I will have a chance to talk about the importance of indoor air quality and the probability of lung cancer from indoor radon. Besides, getting a test kit will allow me to know the radon level in my house, and if high, I can decide independently to mitigate it; thus, I can reduce the risk to get radon-induced lung cancer.

Confidentiality and Anonymity: The information that I will share will remain strictly confidential and will be used solely for this research. The only people who will have access to the research data are the principal researcher and his supervisors. The answers to the open-ended questions may be used verbatim in presentations and publications by anonymizing the identities with pseudonyms and codes. I am aware that the study results will be published in pooled (aggregate) format ensuring anonymity by replacing the personally identifiable information with pseudonyms and codes.

Conservation of data: The surveys data will be stored in a locked safe in the office of principal investigator at the University of Ottawa. On his leaving the university, the supervisor (professor) or his replacement will similarly keep the records stored safe for five years at which time these will be securely destroyed.

Voluntary Participation: I understand that I am under no obligation to participate, and if I choose to participate, I may refuse to answer any question that you do not want to. At any point in time I may withdraw from the survey; then, the information given will be deleted immediately. The completion and return of the questionnaire will imply my consent.

Information about the Study Results: We agree herewith the research findings will be made available to me sending in a password protected file attached with an email.

If you have any questions or require more information about the study itself, you may contact the researcher or his supervisors at the numbers mentioned herein.

The McLaughlin Centre for Population Health Risk Assessment is supporting this study by providing radon test kits. The investigator declares that there is no conflict of interest as to sell or solicit anything or neither there is any other vested issue.

If I have any ethical concerns regarding my participation in this study, I may contact the Protocol Officer for Ethics in Research, University of Ottawa, 550 Cumberland Street, Room 154, (613) 562-5387 or ethics@uottawa.ca.

There are two copies of the consent form, one of which is mine to keep.

Thank you for your time and consideration.

Participant's signature: ___________________________ Date: _______________________

Researcher's signature: ___________________________ Date: ________________________

Appendix 21. Informed consent for paper-based survey (French)

uOttawa

Faculté des sciences de la santé
Faculty of Health Sciences

Université d'Ottawa

Faculté des sciences de la santé
École interdisciplinaire en sciences de la sante

University of Ottawa

Faculty of Health Sciences
Interdisciplinary School in Health Sciences

Formulaire de consentement : Une approche axée sur la santé de la population pour examiner la perception du risque de radon par les résidents d'Ottawa-Gatineau (sur papier)

Names and Institutional Affiliation of the Researchers:

Chercheur principal : Selim M. Khan
Candidat au doctorat en santé de la population
École interdisciplinaire des sciences de la santé
210 Thompson, 25 Université privée
Ottawa, ON, K1N7K4, Université d'Ottawa,
Courriel : xxx
Tél. cellulaire : xxx

Superviseur : Dr. James Gomes, Professeur Agrégé
École interdisciplinaire des sciences de la santé
210 Thompson, 25 Université privée
Université d'Ottawa, Ottawa, ON, K1N7K4
Courriel : xxx
Tél. Bureau : xxx

Co-superviseur : Dr. Samia Chreim, Professeur
École de gestion Telfer, 55, avenue Laurier Est
Université d'Ottawa, Ottawa, ON, K1N65
Courriel : xxx
Tél. Bureau : xxx

Invitation à participer : Je suis invité à participer à cette étude relative à la qualité de l'air intérieur, plus précisément au radon mené par Selim Khan pour sa thèse de doctorat. On m'informe que le radon est un gaz radioactif incolore et inodore provenant du sol et s'infiltrant dans les maisons par le sous-sol. Une fois inhalé, il peut causer le cancer du poumon à long terme. Les enfants et les femmes sont exposés à un risque accru, et le risque est triple pour les fumeurs.

Tel: 613 562 5800
Fax: 613 562 5632
25 University Ptv.
Ottawa, ON, K1N 6N5
Canada

www.uOttawa.ca

Objective et but de l’étude : Je comprends que le but de cette étude est de connaître la perception du risque de santé du radon par les citoyens et la technique d'adaptation appropriée. L'information recueillie aidera à déterminer pourquoi les taux de dépistage et d'atténuation du radon sont demeurés faibles ; ainsi, pour trouver des preuves pour informer les décisions politiques.

Description de la participation : Ma participation à cette étude comprend la réalisation d'un sondage sur papier qui peut prendre environ 30 minutes. Ma signature ci-dessous est une indication de mon consentement à participer à cette enquête. Je comprends que je n'ai pas à répondre à une question que je ne veux pas. Une fois rempli les copies physiques du sondage, je le remettrai au chercheur qui m'a assuré de la stricte confidentialité de toutes mes informations personnellement identifiables.

Droits du participant à la recherche : Je comprends que ma participation à cette étude est volontaire et je n'ai aucune obligation. J'aurai le droit de refuser de répondre à toute question sans crainte de représailles. Je comprends que puisque ma participation à cette étude entraînera le partage volontaire de certaines informations relatives à ma maison, même si elles ne sont pas intimement personnelles, elles peuvent me causer des désagréments (émotionnels ou psychologiques) si quelqu'un du ménage ou de la famille a / eu un cancer du poumon. Je reçois l'assurance du chercheur que tous les efforts seront faits pour minimiser ces risques. Il est clair pour moi qu'à tout moment de l'entrevue, si je ressens de l'inconfort ou du stress, je peux arrêter de répondre à toute question ou me retirer complètement de l'étude. Dans ce cas, l'interview sera terminée et les informations recueillies jusqu'à ce moment seront immédiatement effacées. Pour obtenir de l'aide supplémentaire, je peux communiquer avec un conseiller psychosocial à la ligne d'aide d'Ottawa Public Health (613-722-6914), accessible gratuitement 24 heures par jour, 7 jours par semaine.

Avantages : Ma participation à cette étude améliorera ma compréhension du risque pour la santé de la population liée au radon, ce qui me permettra de mettre à jour mes connaissances sur le risque. J'en saurai plus sur les options de gestion des risques disponibles et leur efficacité. J'aurai l'occasion de parler de l'importance de la qualité de l'air intérieur et de la probabilité de développer un cancer du poumon à l'intérieur du radon. De plus, l'obtention d'un kit de test me permettra de connaître le niveau de radon dans ma maison, et s'il est élevé, je pourrai décider de l'atténuer de manière indépendante ; Ainsi, je peux réduire le risque d'avoir un cancer du poumon induit par le radon.

Confidentialité et anonymat : Les informations que je partagerai resteront strictement confidentielles et seront utilisées uniquement pour cette recherche. Les seules personnes qui auront accès aux données de recherche sont le chercheur principal et ses superviseurs. Les réponses aux questions ouvertes peuvent être utilisées textuellement dans les présentations et les publications en anonymisation les identités avec des pseudonymes et des codes. Je suis conscient que les résultats de l'étude seront publiés en format groupé (agrégé) assurant l'anonymat en remplaçant les informations personnellement identifiables par des pseudonymes et des codes.

Conservation des données : Les données des enquêtes seront conservées dans un coffre-fort verrouillé au bureau du chercheur principal de l'Université d'Ottawa. À sa sortie de l'université, le superviseur (professeur) ou son remplaçant conservera de la même façon les dossiers conservés en lieu sûr pendant cinq ans, après quoi ceux-ci seront détruits en toute sécurité.

Participation volontaire : Je comprends que je n'ai aucune obligation de participer, et si je choisis de participer, je peux refuser de répondre à toute question que vous ne voulez pas. À tout moment, je peux me retirer de l’enquête ; alors, l'information donnée sera effacée immédiatement. L'achèvement et le retour du questionnaire impliqueront mon consentement.

Informations sur les résultats de l’étude : Nous sommes d'accord avec les résultats de la recherche qui seront mis à ma disposition en envoyant un fichier protégé par mot de passe joint à un courriel. Si vous avez des questions ou avez besoin de plus d'informations sur l'étude elle-même, vous pouvez contacter le chercheur ou ses superviseurs aux numéros mentionnés ici.

Le Centre McLaughlin d'évaluation des risques pour la santé des populations appuie cette étude en fournissant des trousses d'analyse du radon. L'enquêteur déclare qu'il n'y a pas de conflit d'intérêts quant à la vente ou la sollicitation de quelque chose ou qu'il n'y a pas d'autre problème.

Si j'ai des préoccupations d'ordre éthique concernant ma participation à cette étude, je peux communiquer avec l'agent de protocole pour l'éthique de la recherche, Université d'Ottawa, 550, rue Cumberland, bureau 154, (613) 562-5387 ou ethics@uottawa.ca.

Il y a deux copies du formulaire de consentement, dont l'une est à moi.

Merci pour votre temps et votre considération.

Signature du participant : __________________________ Date : ______________________

Signature du chercheur : __________________________ Date : ______________________

Appendix 22. Qualitative Interview Protocol (English)

Qualitative Exploration of Radon Health Risk Perception among Ottawa Residents

Interview Guide Interview #________
Date___/___/___

Introduction:

Good morning/afternoon. I want to thank you for taking the time to meet with me today. My name is Selim, a graduate student from the University of Ottawa. I would like to ask about your experiences with indoor air quality. There is no right or wrong answer; I want to learn from your experience. Please be assured that I am not selling or soliciting anything. The interview is voluntary, and your responses will be kept entirely confidential and anonymous. This means that your interview responses will only be shared with research team members and we will ensure that any information we include in our report does not identify you as the respondent. Please note that you don't have to talk about anything you don't want to, and you may end the interview at any time.

The purpose of this interview is to explore residents' perception of radon health risk, and whether and how they decide to manage this risk. I will share the outcome of this research with you.

There are two major parts to this interview. The first part is about your perception of the health risk from radon and the second part is a set of demographic questions. You may stop me and pose any question.

The interview should take less than an hour. I need your consent to go ahead, there is the consent form; let's go over it. Do I have your permission to record the interview? I don't want to miss any of your comments.

Are there any questions about what I have just explained?

First Part: Radon Health Risk Perception

A. **General Awareness:** 1. What do you know about radon (where did you hear, see or learn something about radon)? [Probes: What do you remember about seeing, hearing or attending any radon campaign in your community or workplace? What was that, please describe? Can you also tell me who sponsors or funds those programs or activities?]

B. Perception of Probability, Severity and Synergistic Risk of Radon:

2. What do you know about the harmful health effects of radon?

3. How likely is it that you or a member of your family might get radon-induced lung cancer?

4. In your opinion, how severe is it?

5. What do you know about smoking enhancing/synergizing the harmful effect of radon?

C. Adaptation and Coping Behaviors:

6. How can people find out whether there is a high level of radon in their homes?

7. Have you ever tested your home for radon? [Or thinking of doing so]

[If 'yes', continue below. If 'no', then skip questions 8-10 and restart at Q:11]

8. Do you remember the result of that test?

9. How did you test your home for radon? [Long [term/short term; what was the recommendation got after testing?]

10. If you did, how was the mitigation of your home for radon? [Please tell me about the retesting, outcomes of that and recommendations that you received.]

D. Efficacy in Adapting Behaviors:

11. [If the answer is ‘no’ to Q: 7] what reasons may there be for not testing and fixing one’s home for radon? [Probe: Is there any barrier or challenge you see in fixing your home for radon?]

12. [If the answer is ‘yes’ to Q: 7] what in your opinion, encouraged you to test and mitigate your home for radon? [Probe: How did you overcome those challenges? Did you know or observe anybody doing the test for radon?]

13. How likely is it that you will recommend your friends and relatives to test for radon and to fix their houses once the level is found high?

14. What do you think (worldview) about the radon public health risk? (Probes: Is it an overall societal problem [communitarian] or just an individual [individualist] issue; should government be responsible for tackling the issue [egalitarian] or only individual homeowner/tenants [hierarchic] are responsible)

We are done with the main part of the interview. As I said, I have some demographic questions, but please rest assured, all personally identifiable information will remain confidential, and when I write the report, personal identifications will be removed, and the information will be generalized, nobody will know who said what.

Second Part: Demographic questions:

1. What is your age range: 18-35, 36-45, 46-60, and 60+?

2. Race: [As you like to identify yourself]

3. What is your education level: some elementary, some high school, completed high school, post-secondary, college, bachelor, graduate studies?

4. How many rooms are there in your home? How many people live in this home?

5. Does your household currently include any children under 16 years of age?

6. What is your occupation (current/previous)?

7. For statistical purposes only, we need information about your household income. Please tell me which of the following categories applies to your total household income for the year 2016? [Less than $40,000, $40,000 to $75,000, $75,000 to $100,000, $100,000 to $150,000, $150,000 and over, DK/NA]

8. And finally, to better understand how results vary by region, may I have your 3-digit postal code?

Additional question: Is there anything more you would like to add?

I'll be analyzing the information you and others gave me and preparing a draft report to my thesis committee in a few months. I'll be happy to send you a copy to review if you are interested.

This completes the interview. Thank you very much for your time.

Can I come back to you, if more information is needed?

In case my supervisor(s) would like to verify that I conducted this interview, may I have your first name?

First Name: ______________________________

Phone number: email:

To Record: Gender: Male, Female, and Other; Study group: I or II

Reference. Based on the analysis of data from Health Canada survey 2007, 2011 with permission and access got from Health Canada and Public Health Agency of Canada through ATIP Request# A-2016-00315.

Appendix 23. Qualitative Interview Protocol (French)

Titre: Une approche axée sur la santé de la population pour examiner la perception du risque de radon par les résidents d'Ottawa-Gatineau

Guide d'entrevue Entretien #__________

Date____/_____/___

Introduction :

Bonjour / Bon après-midi. Je tiens à vous remercier d'avoir pris le temps de me rencontrer aujourd'hui. Je m'appelle Selim, je suis un étudiant diplômé de l'Université d'Ottawa. J'aimerais vous poser des questions sur vos expériences concernant la qualité de l'air intérieur. Il n'y a pas de réponse juste ou fausse, je souhaite juste apprendre de votre expérience. Soyez assuré que je ne vends ou ne sollicite rien. L'entretien est volontaire et vos réponses resteront entièrement confidentielles et anonymes. Cela signifie que vos réponses aux entrevues ne seront partagées qu'avec les membres de l'équipe de recherche et nous veillerons à ce que toute information que nous incluons dans notre rapport ne vous identifie pas en tant que répondant. Veuillez noter que vous n'êtes pas obligé de parler de ce que vous ne voulez pas et que vous pouvez mettre fin à l'interview à tout moment.

Le but de cette entrevue est d'explorer la perception des résidents sur les risques pour la santé liée au radon, et comment ils décident de gérer ce risque. Je partagerai les résultats de cette recherche avec vous.

Il y a deux parties principales dans cette interview : la première partie porte sur votre perception du risque pour la santé du radon, et la deuxième partie est un ensemble de questions démographiques. Vous pouvez m'arrêter quand vous voulez et poser n'importe quelle question. L'entrevue devrait prendre moins d'une heure.

J'ai d'abord besoin de votre consentement pour aller de l'avant, voici le formulaire de consentement. Me donnez-vous votre permission pour enregistrer l'interview ? Je ne voudrais manquer aucun détail de vos commentaires.

Avez-vous des questions sur ce que je viens d'expliquer ?

Première partie : Perception du risque pour la santé du radon

A. Conscience générale :

1. Que savez-vous du radon (où avez-vous entendu, vu ou appris quelque chose sur le radon) ?

[Sondage : Vous rappelez-vous avoir vu, entendu ou assisté à une campagne de radon dans votre communauté ou votre lieu de travail ? Qu'est-ce que c'était ? Pouvez-vous le décrire ? Pouvez-vous également me dire qui parraine ou finance ces programmes ou activités ?]

B. Perception de la probabilité, de la gravité et du risque synergique de radon :

2. Que savez-vous des effets nocifs sur la santé du radon ?

3. Quelle est la probabilité que vous ou un membre de votre famille ayez un cancer du poumon induit par le radon ?

4. À votre avis, quelle est sa gravité ?

5. Que savez-vous à propos du tabagisme améliorant / l'effet synergiste nocif du radon ?

C. Adaptation et comportements d'adaptation

6. Comment les gens peuvent-ils savoir s'il y a un niveau élevé de radon dans leur maison ?

7. Avez-vous déjà testé votre maison pour le radon ? [Ou pensé à le faire ?]

[Si 'oui', continuez ci-dessous. Si 'non', sautez les questions 8-10 et recommencez à Q : 11]

8. Vous souvenez-vous du résultat de ce test ?

9. Comment avez-vous testé votre maison pour le radon ? [Long-terme / court terme ; Quelle était la recommandation après les tests ?]

10. Si vous l'avez fait, quels ont été les résultats de votre maison pour le radon ? [S'il vous plaît parlez-moi du re-testing, des résultats détaillés et des recommandations que vous avez reçues.]

D. Efficacité dans l'adaptation des comportements :

11. [Si la réponse est non à Q : 7] Quelles raisons peut-il y avoir pour ne pas tester et réparer sa maison pour le radon ? [Sondage : Y a-t-il une barrière ou un défi que vous voyez dans la réparation de votre maison pour le radon ?]

12. [Si la réponse est « oui » à Q : 7] Qu'est-ce qui, à votre avis, vous a encouragé à tester et à atténuer votre maison pour le radon? [Question : Comment avez-vous surmonté ces défis ? Connais-tu ou as-tu observé quelqu'un qui fait le test du radon ?]

13. Quelle est la probabilité que vous recommandiez vos amis et votre famille pour tester le radon et réparer leur maison une fois le niveau trouvé ?

....

14. Que pensez-vous (vision du monde) du risque de santé publique lié au radon ? (Sondage : S'agit-il d'un problème sociétal global [communautaire] ou d'un problème individuel [individualiste], le gouvernement devrait-il être responsable de la question [égalitaire] ou seulement les propriétaires individuels / locataires [hiérarchiques] sont-ils responsables ?

Nous avons terminé avec la partie principale de l'interview. Comme je l'ai dit avant, j'ai encore quelques questions démographiques, mais soyez assurés que toutes les informations personnelles resteront confidentielles, et lorsque j'écrirai le rapport, les identifications personnelles seront supprimées et l'information généralisée, personne ne saura qui a dit quoi.

Deuxième partie : questions démographiques

1. Quelle est votre tranche d'âge : 18-35, 36-45, 46-60, 60+

2.Race : [Comme vous aimez vous identifier]

3. Quel est votre niveau d'études : un niveau élémentaire, un niveau secondaire, un niveau d'études secondaire, postsecondaire, collégial, baccalauréat, études supérieures ?

4. Combien de pièces y a-t-il dans votre maison ? Combien de personnes vivent dans cette maison ?

5. Votre ménage comprend-il actuellement des enfants de moins de 16 ans ?

6. Quelle est votre profession (actuelle / précédente) ?

7. À des fins statistiques seulement, nous avons besoin d'informations sur le revenu de votre ménage. Veuillez me dire laquelle des catégories suivantes s'applique au revenu total de votre ménage pour l'année 2016 ? [Moins de 40 000 $, 40 000 $ à 75 000 $, 75 000 $ à 100 000 $, 100 000 $ à 150 000 $, 150 000 $ et plus, NSP / SO]

8. Enfin, pour mieux comprendre comment les résultats varient selon la région, puis-je avoir votre code postal à trois chiffres ?

Question supplémentaire : Y a-t-il autre chose que vous aimeriez ajouter ?

J'analyserai les informations que vous et d'autres m'ont donnée et préparée un projet de rapport pour mon comité de thèse dans quelques mois. Je serai heureux de vous envoyer une copie pour examiner si vous êtes intéressé.

Ceci termine l'interview. Merci beaucoup pour votre temps.

Puis-je revenir vers vous, si plus d'informations sont nécessaires ?

Au cas où mon superviseur (s) voudrait vérifier que j'ai réellement mené cette interview, puis-je avoir votre prénom ?

Prénom : ______________________________

Numéro de téléphone : email :

Enregistrer :

Sexe : Homme, Femme, Autre

Groupe d'étude : I ou II

Référence. D'après l'analyse des données de l'enquête de Santé Canada de 2007, 2011, Santé Canada et l'Agence de la santé publique du Canada ont obtenu la permission et l'accès dans le cadre de la demande d'AIPRP no A-2016-00315.

Appendix 24. Survey Questionnaire (English)

A Population Health Approach to Examine of Ottawa-Gatineau Residents' Perception of Radon Health Risk

Q1. I certify that I am an adult above the age of 18 and residing at this address for at least one year. I have volunteered to participate in this survey which will contribute to the generation of new academic knowledge in understanding public health perception to radon exposure. Herewith, I consent to participate in this survey. I may have a look over the full 'Implied consent form' before proceeding. I am assured that the confidentiality of all my personally identifiable information will be strictly maintained by the researcher.

[We value your response and care about the quality of our survey data and hope to receive the most accurate measures of your opinions, so it is important to us that you thoughtfully provide your best answer to each question in this survey.]

[This survey is about indoor air quality, specifically about radon. If you have not heard of radon at all before today, you may please visit Health Canada's Radon website before taking this survey].

01 - Yes

02 - No

Q2. Do you own your home or is it rented?

02 – Rented

01 – Owned

Q3. Do you live in a home with a living space on the basement or ground floor? (can check more than one options)

01 – Yes, my home has a living space on the basement

02 – Yes, my home has a living space on the ground floor

03 - No, I/we live on the upper floor but pass over four hours per day on the ground floor or at the basement

04 - No, I/we live in an upper level residence with no time being spent on the ground or at the basement

99 – Don’t know/ Not applicable

Q4. How long have you been living in your current home?

01 – Less than one year

02 – Between one to three years

03 – Between three to five years

04- Over five years (please mention the number of years here:

99 – Don’t know/ Not applicable

Q5. Does a child or anybody live or spend more than four hours per day in the basement or ground floor?

01- Yes

02- No

99 – Don’t know/ Not applicable

Q6. Number of children and adult living or spend more than four hours per day in the basement or ground floor? (Please check all that may apply)

01 – Under five, how many.........

02 – Five to twelve, how many.........

03 - Thirteen to eighteen, how many.........

04- Over eighteen, how many.........

97- None/Prefer not to answer

Q7. Currently or at some point of time in the past have you been concerned about the indoor air quality in your home?

01 – Yes, concerned currently

02 – Yes, concerned in the past

03 – Never concerned

99 – Don't know/ Not applicable

Q8. What is/was the source of your concern about the air quality in your home? (please check all that may apply)

01 – Dust/dust mites

08 – Radon

02 – Mold

03 – Second-hand smoke/tobacco/smokers in the home

98 – Other, please specify...........

99 – Don't know/ Not applicable

Q9. Are you concerned about the radon health risk from radon exposure?

01 – Yes

02 – No

03 – I have not heard of radon before today

Q10. What are your concerns about radon? (please check all that may apply)

04- Bad for children and women

03- Cause respiratory problems

01- Radon is bad for health

02- Radon causes cancer

99 – Don't know/ Not applicable

Q11. Where did you first hear or see something about radon? (please check all that may apply)

04 – Health Canada (flyers, brochures)

01 – Family doctor/general practitioner

02 – Media (TV, Newspaper, Magazine)

07 – WHO's handbook

03 – Internet, site..............(if you can remember)

98 – Other, please specify ___________

99 – Don't know/ Not applicable

Q12. Indicate what describes radon gas the best from the given options: (please check all that may apply)

03 – A gas that comes from carpets, furniture and paints

02 – A radioactive gas degrades from radium and uranium

01 – A gas that comes from natural gas in furnaces and water heaters

04 – A gas that comes from the ground and causes lung cancer

98 – Other, please specify ________

99 – Don't know/ Not applicable

Q13. How likely radon may cause any harm to your or any of your family member's health?

01 Extremely likely

03 Neither likely nor unlikely

05 Extremely unlikely

02 Possibly

04 Possibly not

Q14. Does radon cause any severe or adverse health effect?

02-Seriously affects health

03-Somewhat seriously affect health

04-Nothing serious about radon

01-Very seriously affects health

Q15. Do you consider radon to be a threat to your health or and your family's health?

04-Unlikely

01- Very likely

03-Not likely

02-Likely

05- Very unlikely

Q16. Have you ever tested your home for radon?

01- Yes

02 - No

99 – Don’t know/ Not applicable

Q17. If you have already tested your home for radon, how long had the test kit been placed in your home?

01 – A couple of days

02 – Three months (90 days) or longer

98 – Other, please specify ______

99 – Don't know/No answer

Q18. Did you fix (mitigate) your home for radon?

01- Yes

01- No

99 – Don’t know/ applicable

Q.19 Did you retest your home after mitigation?

01- Yes

02- No

99- DK/NA

Q20. (If you have not yet done) How likely will you do the test for your home for radon?

(Intention to test)

04 Unlikely

01 Very likely

03 Not likely

02 Likely

05 Very unlikely

Q21. If a radon test was done in your home and the level found high, how likely would you take action to have the radon level reduced?

03- Neither likely nor unlikely

02- Possibly likely

05- Extremely unlikely

01- Extremely likely

04- Possibly unlikely

Q22. If unlikely, what is the reason for not taking action? (please check all that may apply)

01 – Local radon levels low/moderate/not a problem

03 – Lack of information/don't know what to do

02 – Not worried about radon/not enough of a risk

98 – Other, please specify ________________

99 – Don't know/ Not applicable

04-Too expensive/cannot afford

Q23. Do you know how to test the radon level in your home? (please check all that may apply)

01 – Get a company or radon professional to do it

03- Ask the government to do it

02 – Buy a kit and do it yourself

98 – Other, please specify ____________

99 – Don't know/ Not applicable

Q24. If there is an inexpensive and cheap way to test radon, how likely are you to do that?

03 - Neither likely nor unlikely

05- Extremely unlikely

04 - Possibly not

01 - Extremely likely

02 - Possibly

Q25. How likely is it that you will recommend your friends and relatives to test their houses for radon?

02- Possibly

01- Extremely likely

05- Extremely unlikely

04- Possibly not

03- Neither likely nor unlikely

Q26. From your own point of view (worldview), which of the following statement(s) will you select regarding the health risk of radon?

02. Radon affects individual persons, so they (homeowners or tenants) are responsible for fixing it

03. Radon is a natural hazard; government cannot be blamed for it. It's a shared responsibility of homeowners as well as of government

04. It is a population health problem, governments and/or mandated agencies are responsible for fixing it.

01. It is an overall problem from coast to coast; property owners and tenants should get support from the governments to fix it.

Q27. Do you know how people can reduce the amount of radon in their homes? (Check all that apply)

06 – Increase ventilation/use mechanical or heat recovery/HRV ventilator/exchanger	05 – Cover exposed soil in crawlspaces with sealed barriers
01 – Sealing cracks or other openings in foundations	98 – Other, please specify ____
02 – Install a radon reduction system/sub-slab depressurization system	99 – Don't know/ Not applicable
03 – Sealing cracks or other openings in foundations	04 - Cover or seal sump pit holes

Q28. How many people you know who have tested their homes for radon?

01- One

02- More than one (please mention the number here: ….)

99 – None/ Don't know/ Not applicable

Q29. What else you know about radon? Or If you want to add your opinion about radon public health risk, please feel free to write down here:

………………………….

…………………………..

………………………….

Q30. Does anybody smoke cigarette in your home?

01 – Yes, self

02 – Yes, someone else in household

03 – Yes, both self and others

04 – No, no one

99 – Don't know/ Not applicable

Q31. Have you or anyone else in your household ever been diagnosed with lung cancer?

01 – Yes – myself

02 – Yes – other

03 – No

99 – Don't know/ Not applicable

Q32. Is/Was that other person a smoker?

01 – Yes

02 – Former smoker but already quit

03 – No, was not a smoker ever

99 – Don’t know/ Not applicable

Q33. How do you rate the risk of smoking and radon combined compared to the risk of smoking alone?

01 - Higher risk

02 - Same risk

03 - Lower risk

04 - No relation

05 - Don’t know

Q34. Q.34 to Q.39 are for statistical purpose only; confidentiality of all personally identifiable information is guaranteed under the Tri-Council Privacy Statement (Privacy Act):

What is the highest level of education you have completed?

01 – Elementary school

02 – Some high school

03 – Completed high school

04 – Some community college/technical college/CEGEP

05 – Completed community college/technical college/CEGEP

06 – Some university

07 – Completed university (undergrads)

08 – Post-graduate degree (Master, PhD)

09 – Post-doctorate

10 – No schooling

97 – Prefer not to answer

Q35. What is your age group?

01 - 18 to 24 year	03 - 35 to 44 year	05 - 55 to 64 year
02 - 25 to 34 year	04 - 45- 54 year	06 - 65 and above

Q36. Please record your gender:

01-Male

02-Female

03-I identify myself as…

Q37. Please record your ethnicity/race:

(Besides checking a given option, you may add a bit detail into the box, if you want to specify).

01- European Canadian

03 - Visible minority, please specify (e.g. African, Asian, Latino, and Caribbean):

02 - Aboriginal Canadian, e.g. (First Nations, Metis, and Inuit):

97- Prefer not to answer

Q38. Would you please mention which of the following categories applies to your total household income for the previous year?

01 – Less than $40,000	04 – $101,000 to just under $150,000
02 – $41,000 to just under $75,000	05 – $151,000 and over
03 – $76,000 to just under $100,000	97 – Prefer not to answer

Q39. And finally, to better understand how results vary by region, may I have your 6-digit postal code?

01- Please enter here:…… …… …….

Q40. Do you want the researcher sends you a copy of the final report of this survey?

01- Yes, please add your email here (it will not be used for any other purpose):

02- No, thanks.

Q41. Please visit 'Take Action on Radon' website for more information.

Appendix 25. Survey Questionnaire (French)

Enquête : Une approche axée sur la santé de la population pour examiner la perception du risque de radon par les résidents d'Ottawa-Gatineau

Q1. Je certifie que je suis un adulte de plus de 18 ans et que je réside à cette adresse depuis au moins un an. Je me suis porté volontaire pour participer à cette enquête qui contribuera à la génération de nouvelles connaissances universitaires permettant de comprendre la perception de la santé publique par rapport à l'exposition au radon.

Par la présente, je consens à participer à cette enquête. Je peux jeter un coup d'œil sur le «formulaire de consentement implicite» complet avant de poursuivre. Je suis assuré que le chercheur maintiendra strictement la confidentialité de toutes mes informations personnellement identifiables.

[Nous apprécions votre réponse et nous nous soucions de la qualité des données de notre sondage et espérons recevoir les mesures les plus précises de vos opinions. Il est donc important pour nous que vous donniez votre meilleure réponse à chaque question de ce sondage.]

[Cette enquête porte sur la qualité de l'air intérieur, en particulier sur le radon. Si vous n'avez jamais entendu parler du radon avant aujourd'hui, vous pouvez visiter le site Web sur le radon de Santé Canada avant de répondre à cette enquête.]

01 - oui

02 - Non

Q2. Êtes-vous propriétaire de votre maison ou est-il loué?

02 - Loué

01 - Possédé

Q3. Vivez-vous dans une maison avec un espace de vie au sous-sol ou au rez-de-chaussée? (peut vérifier plus d'une option)

01 - Oui, ma maison a un espace de vie au sous-sol

02 - Oui, ma maison a un espace de vie au rez-de-chaussée

03 - Non, je vis / nous vivons à l'étage supérieur mais passons plus de quatre heures par jour au rez-de-chaussée ou au sous-sol

04 - Non, j'habite / nous habitons dans une résidence de niveau supérieur sans temps passé au sol ou au sous-sol

99 - Ne sait pas / sans objet

Q4. Depuis combien de temps vivez-vous dans votre maison actuelle?

01 - Moins d'un an

02 - Entre un et trois ans

03 - Entre trois et cinq ans

04- Sur cinq ans (veuillez indiquer le nombre d'années ici:

99 - Ne sait pas / sans objet

Q5. Est-ce que quelqu'un vit ou passe plus de quatre heures par jour au sous-sol ou au rez-de-chaussée?

01- oui

02- Non

99 - Ne sait pas / sans objet

Q6. Nombre d'enfants et d'adultes vivant ou passant plus de quatre heures par jour au sous-sol ou au rez-de-chaussée? (Veuillez cocher tout ce qui peut s'appliquer)

01 - Moins de cinq ans, combien ....

02 - Cinq à douze, combien ....

03 - Treize à dix-huit ans, combien ....

04- Plus de dix-huit ans, combien ....

97- Aucun(e) / Préfère ne pas répondre

Q7. Actuellement ou à un moment dans le passé, êtes-vous préoccupé par la qualité de l'air intérieur de votre maison?

01 - Oui, actuellement concerné

02 - Oui, inquiet dans le passé

03 - Jamais concerné

99 - Ne sait pas / sans objet

Q8. Quelle est / était la source de vos préoccupations concernant la qualité de l’air de votre maison? (veuillez cocher tout ce qui peut s'appliquer)

01 - Poussière / acariens

03 - Fumée secondaire / tabac / fumeurs à la maison

08 - Radon

98 - Autre, veuillez spécifier ....

02 – Mould

99 - Ne sait pas / Sans objet

Q9. Êtes-vous préoccupé par le risque que présente le radon pour la santé lié à l'exposition au radon?

01 - oui

02 - Non

03 - Je n'ai pas entendu parler du radon avant aujourd'hui

Q10. Quelles sont vos préoccupations concernant le radon? (veuillez cocher tout ce qui peut s'appliquer)

04- Mauvais pour les enfants et les femmes

03- Causer des problèmes respiratoires

01- Le radon est mauvais pour la santé

02- Le radon cause le cancer

99 - Ne sait pas / sans objet

Q11. Où avez-vous entendu parler du radon pour la première fois? (veuillez cocher tout ce qui peut s'appliquer)

04 - Santé Canada (dépliants, brochures) 03 - Internet, site .... (si vous vous en souvenez)

01 - Médecin de famille / médecin généraliste 98 - Autre, veuillez préciser ____________

02 - Médias (télévision, journal, magazine) 99 - Ne sait pas / sans objet

07 - Manuel de l'OMS

Q12. Indiquez ce qui décrit le mieux le radon parmi les options proposées: (cochez toutes les réponses possibles)

03 - Un gaz provenant de tapis, de meubles et de peintures 04 - Un gaz provenant du sol et causant le cancer du poumon

02 - Un gaz radioactif se dégrade du radium et de l'uranium 98 - Autre, veuillez préciser _________

01 - Un gaz provenant du gaz naturel dans les chaudières et les chauffe-eau 99 - Ne sait pas / Sans objet

Q13. Quelle est la probabilité que le radon puisse nuire à votre santé ou à celle d'un membre de votre famille?

01 extrêmement probable

03 Ni probable ni improbable

05 Extrêmement improbable

02 éventuellement

04 Peut-être pas

Q14. Le radon a-t-il des effets nocifs ou sévère sur la santé?

02-affecte gravement la santé

03-Assez sérieusement affecter la santé

04-Rien de sérieux à propos du radon

01-affecte très sérieusement la santé

Q15. Considérez-vous le radon comme une menace pour votre santé ou celle de votre famille?

04-Peu probable

01- Très probable

03-Peu probable

02-probable

05- Très peu probable

Q16. Avez-vous déjà testé le radon dans votre maison?

01- oui

02 - Non

99 - Ne sait pas / sans objet

Q17. Si vous avez déjà testé votre maison pour le radon, depuis combien de temps le kit de test a-t-il été placé dans votre maison?

01 - Quelques jours

02 - Trois mois (90 jours) ou plus

98 - Autre, veuillez préciser ______

99 - Ne sait pas / pas de réponse

Q18. Avez-vous réparé votre maison contre le radon?

01- oui

01- Non

99 - Ne sait pas / n'est pas applicable

Q.19 Avez-vous retesté votre test après l'atténuation?

01- oui

02- Non

99- NSP / SO

Q20. (Si vous ne l'avez pas encore fait) Quelle est la probabilité que vous fassiez le test du radon dans votre maison? (Intention de tester)

04 Peu probable

01 Très probable

03 peu probable

02 probable

05 Très improbable

Q21. Si un test de radon était effectué chez vous et que le niveau était jugé élevé, quelle serait votre probabilité de prendre des mesures pour réduire le niveau de radon?

03- Ni probable ni improbable

02- Probablement probable

05- Extrêmement improbable

01- Extrêmement probable

04- Probablement improbab

Q22. Si peu probable, quelle est la raison pour ne pas agir? (veuillez cocher tout ce qui peut s'appliquer)

01 - Niveaux locaux de radon faibles / modérés / ne posent pas problème 98 - Autre, veuillez préciser ________________

03 - Manque d'information / ne sait pas quoi faire 99 - ne sait pas / sans objet

02 - Pas préoccupé par le radon / pas assez de risque 04-Trop cher / ne peut se permettre

Q23. Savez-vous comment mesurer le niveau de radon dans votre maison? (veuillez cocher tout ce qui peut s'appliquer)

01 - Demandez à une entreprise ou à un professionnel du radon de le faire

03- Demander au gouvernement de le faire

02 - Achetez un kit et faites-le vous-même

98 - Autre, veuillez préciser ____________

99 - Ne sait pas / sans objet

Q24. S'il existe un moyen peu coûteux et peu coûteux de tester le radon, quelle est votre probabilité de le faire?

03 - Ni probable ni improbable

05- Extrêmement improbable

04 - Peut-être pas

01 - Extrêmement probable

02 - éventuellement

Q25. Quelle est la probabilité que vous recommandiez à vos amis et à votre famille de tester le radon dans leurs maisons?

02- éventuellement

01- Extrêmement probable

05- Extrêmement improbable

04- Peut-être pas

03- Ni probable ni improbable

Q26. De votre propre point de vue, lequel des énoncés suivants choisirez-vous concernant le risque pour la santé que présente le radon?

02. Le radon affecte des personnes individuelles. Par conséquent, elles (propriétaires ou locataires) sont responsables de sa réparation.

03. Le radon est un danger naturel. le gouvernement ne peut être blâmé pour cela. C’est une responsabilité partagée des propriétaires et du gouvernement

04. C'est un problème de santé de la population, les gouvernements et / ou les agences mandatées sont responsables de le résoudre.

01. C'est un problème général d'un océan à l'autre; les propriétaires et les locataires devraient obtenir l'appui des gouvernements pour résoudre ce problème.

Q27. Savez-vous comment les gens peuvent réduire la quantité de radon dans leurs maisons? (Cochez toutes les cases)

06 - Augmentez la ventilation / utilisez un ventilateur / récupérateur de chaleur / récupérateur de chaleur / VRC 05 - Couvrez les sols exposés dans les vides sanitaires avec des barrières scellées

01 - Crevasses ou autres ouvertures dans les fondations 98 - Autre, veuillez préciser ____

02 - Installer un système de réduction du radon / dépressurisation des sous-dalles 99 - Ne sait pas / Non applicable

03 - Crevasses ou autres ouvertures dans les fondations 04 - Couvrir ou sceller les trous de puisard

Q28. Combien de personnes connaissez-vous qui ont testé leur maison pour le radon?

01- un

02- Plus d'un (veuillez mentionner le numéro ici: ….)

99 - Aucune / Ne sait pas / Sans objet

Q29. Que savez-vous d'autre sur le radon? Si vous souhaitez ajouter votre avis sur les risques pour la santé publique liés au radon, n'hésitez pas à écrire ici:

…………………………….

……………………………..

…………………………….

Q30. Est-ce que quelqu'un fume la cigarette chez vous?01 - Oui, soi-même

02 - Oui, quelqu'un d'autre dans le ménage

03 - Oui, soi et les autres

04 - Non, personne

99 - Ne sait pas / sans objet

Q31. Avez-vous déjà diagnostiqué un cancer du poumon ou un autre membre de votre ménage?

01 - Oui - moi-même

02 - Oui - autre

03 - Non

99 - Ne sait pas / sans objet

Q32. Cette autre personne est-elle un fumeur?

01 - oui

02 - Ancien fumeur mais déjà fumeur

03 - Non, je n'ai jamais fumé

99 - Ne sait pas / sans objet

Q33. Comment évaluez-vous le risque de tabagisme et de radon combiné par rapport au risque de fumer seul?

01 - Risque plus élevé

02 - Même risque

03 - Risque réduit

04 - Pas de relation

05 - Je ne sais pas

Q34. Les questions Q.34 à Q.39 servent uniquement à des fins statistiques; La déclaration de confidentialité des trois Conseils (Loi sur la protection des renseignements personnels) garantit la confidentialité de tous les renseignements personnels identifiables:

Quel est le niveau de scolarité le plus élevé que vous avez atteint?

01 - École primaire

07 - Études universitaires complétées

02 - Quelques années de lycée

08 - Diplôme de troisième cycle (maîtrise, doctorat)

03 - Études secondaires terminées

09 - Post-doctorat

04 - Certains collèges communautaires / collèges techniques / cégeps

10 - Aucune scolarité

05 - Collège communautaire / collège technique / Cégep

97 terminé - Préfère ne pas répondre

06 - Un peu universitaire

Q35. Quel est votre groupe d'âge?

01 - 18 à 24 ans

03 - 35 à 44 ans

05 - 55 à 64 ans

02 - 25 à 34 ans

04 - 45 à 54 ans

06 - 65 ans et plus

Q36. S'il vous plaît enregistrer votre sexe:

01-mâle

02-femme

03-Je m'identifie comme…

Q37. Veuillez enregistrer votre appartenance ethnique / race:

(En plus de cocher une option donnée, vous pouvez ajouter un détail dans la case, si vous voulez spécifier).

01- Canadien européen

03 - Minorité visible, veuillez préciser (par exemple, Afrique, Asie, Amérique latine et Caraïbes):

02 - Canadien autochtone, p. Ex. (Premières nations, métis et inuits):

97- Préfère ne pas répondre

Q38. Pourriez-vous préciser laquelle des catégories suivantes s'applique au revenu total de votre ménage pour l'année précédente?

01 - Moins de 40 000 $

04 - 100 000 $ à un peu moins de 150 000 $

02 - 40 000 $ à un peu moins de 75 000 $ 05 - 150 000 $ et plus

03 - 75 000 $ à un peu moins de 100 000 $

97 - Préfère ne pas répondre

Q39. Et enfin, pour mieux comprendre la variation des résultats selon les régions, puis-je avoir votre code postal à 6 chiffres?

01- Veuillez entrer ici: …… …… …….

Q40. Voulez-vous que le chercheur vous envoie une copie du rapport final de cette enquête?

01- Oui, veuillez ajouter votre email ici (il ne sera utilisé à aucune autre fin):

02- non merci

Q41. Veuillez visiter le site Web «Agissez contre le radon» pour plus d'informations.

Appendix 26. Recruitment Notice (Qualitative Interview)

Research Participants Needed

Why are we doing this study?

Canadians spend over 90% of time indoors. Knowing about and maintaining indoor air quality is crucial for our health, more importantly for children and women. This study aims to explore your perception about indoor radon gas that will help support policy recommendations.

Who can participate in this study?

Homeowners and tenants in Ottawa and neighbourhoods (adult only)

What do you do?

Take part in an interview, it takes about 30-40 minutes

Where?

Preferably at your home or nearby public place at your preference

How will my data be used?

Your data will be anonymized. Kept in a safe for 5 years and then destroyed.

How to join?

Please call or email to Selim Khan

Email: xxx

Tell: xxx

Appendix 27. Recruitment ad.

uOttawa
Faculté des sciences de la santé
Faculty of Health Sciences

Looking for Research Participants

Health Canada Santé Canada

Why are we doing this study?

- Canadians spend over 90% of their time indoors.
- Indoor air quality is crucial for our health, more so for children.
- This study aims to explore your perception about indoor radon gas that will help support policy.

Who can participate in this studv?

- Homeowners and tenants from Ottawa-Gatineau and neighborhoods
- Living in a house for at least one year that have a used basement or living space on the ground floor.

How, where and when?

- Face to face interview
- At your preferred place and time

Participate in an interview that takes about 45- 60 minutes.

What do you do?

What will I get?

- Acquire knowledge about indoor air quality, risks, & way outs
- Satisfaction for contributing to knowledge generation
- A free test kit is available to voluntarily test your house for radon

Or,
Email to

Appendix 28. Recruitment Notice (Survey)

Research Participants Needed

Why are we doing this study?

Canadians spend over 90% of time indoors. Knowing about and maintaining indoor air quality is crucial for our health, more importantly for children and women. This study aims to quantify your perception about indoor radon gas that will help support policy recommendations.

Who can participate in this study?

Homeowners and tenants in Ottawa and neighbourhoods (adult only i.e. Age 18 and above)

What do you do?

To participate in a survey, it takes about 30-40 minutes

Where?

Either online or with pen-and pencil as convenient to you, at your preferred place

How will my data be used?

Your data will be anonymized. Kept in a safe for 5 years and then destroyed.

How to join the study?

Please call or email to Selim Khan

Email: xxx

Tell: … … ….

Appendix 29. Radon mitigation techniques around the globe with the degrees of effectiveness

Country	Radon remediation methods that showed varying degrees of effectiveness
USA	a. An expert panel supported by the US Centers for Disease Control and Prevention (CDC) and the National Center for Healthy Housing in the USA reviewed radon air mitigation through active soil depressurization. Evidence gathered from seven studies (each enrolled from 73 to 238 houses) showed that active radon mitigation using SSDS is the most effective in reducing radon below the guideline level of 4 pCi/L or 148 Bq/m^3 (Sandel et al., 2010). b. A previous EPA review concluded that 97% of houses with high baseline radon levels (76% had baseline radon levels ≥ 10 pCi/L) could be remediated with the active SSDS to less than 4 pCi/L (Burkhart & Kladder, 1991). c. Similarly, an independent experimental study conducted in an unoccupied research house in Wisconsin, USA measured both radon and winter moisture from soil gases. They applied an active SSDS and showed up to 96.5% and 75% efficiency in reducing radon gas and soil moisture (Boardman & Glass, 2015).
Canada	a. In southern Alberta, 90 homes with an average radon level of 575 Bq/m^3 were mitigated with SSDS with the radon-impermeable membrane in some cases. They successfully reduced radon level to an average of 32.5 Bq/m^3. The most effective radon mitigation for a recorded level of 3441 Bq/m^3 was 97.5% (Stanley et al., 2017). b. An intervention study in nine houses in Quebec installed SSDS with ground discharge and fan in the basement and roof discharge and fan in the attic. This paper presents a detailed comparative analysis of the radon condensation problems, reduction efficiency and cost-effectiveness. Both the mitigations scenarios were successful in reducing radon. The system with fans at the basement and attic levels showed the effectiveness of 89% and 95% respectively (Brossard, Ottawa, Falcomer & Whyte, 2015).
UK	a. Sump Depressurization. et al. (2008) monitored 170 UK homes for radon over three-month pre and post-remediation using track-etch detectors and found mean radon concentrations 487 Bq/m^3 before mitigation. After installing sump depressurization (a form of SSDS), about 100% of homes returned to the post-remediation mean radon level 64.6 Bq/m^3 that is below the UK domestic action level (200 Bq/m^3). The finding corresponds with those of other sump effectiveness studies

	in the UK (Naismith, Miles & Scivyer, 1998; Wilson, Dundey & Gammage, 1994; Howarth, 2001) that showed effects ranging from 70% to 99%. b. Active ventilation: Marley and Phillips (2001) measured average levels of radon and progeny in four buildings in Northamptonshire, the UK using track-etched passive detectors and a Thompson and Nielson radon working level meter respectively. Radon measurements were taken for four-week periods at three sites and four months at one place. Two active mechanical ventilation systems exchanging indoor air were compared: a) Air conditioning (AC, in 2 sites) and wet central heating (CH, in 2 sites) without air conditioning. The reduction factors (initial **concen**tration divided by that after remediation) of radon and progeny ranged from 4 to 6 (radon being reduced from 35 to 40 Bq/m^3 when the air conditioning was off to 5 to 7 Bq/m^3 with the air conditioning on). 'Wet' CH reduced radon levels by initiating change in advective gas flow. This occurred more gradually and less effectively than with AC. c. Passive ventilation: Wang and Ward (1997) examined change in radon level with passive air exchange rates in an occupied Northern England single-family dwelling. Hourly radon measures were taken in the cellar, bedrooms, living room, hallway and lounge once every three days when a different ventilation method was employed. The three consecutive ventilations methods were: a. Natural ventilation, b. Exhaust ventilation and c. Supply ventilation. They noted that the natural ventilation was not efficient in reducing radon levels, but both extract ventilation and supply ventilation were useful. Whereas, under conditions of low air change rates, extract ventilation was more effective than supply ventilation
France	Diallo, Collignan, & Allard (2015) developed an airflow model to evaluate the effectiveness of active and passive SDS. In an analytical method, they examined mitigation systems with different substructures where models were integrated into multizone airflow and heat transfer building codes. They took into account climate conditions (stack effect and wind), building envelope characteristics and ventilation systems. The preliminary field verification results for the extracted flow by the SDS in an experimental building were noted. The efficiency of the SDS with supply ventilation was about 100%. For balanced and natural ventilation, it was 90%, and for exhaust ventilation, the average efficiency was -67%. The negative efficiency meant that the exhaust ventilation system exacerbated the entry of the pollutant in the building, compared to the reference situation.
Ireland	Study in Cork County, 234 homes exceeding the reference level (200 Bq/m^3) were remediated by using an active sump. The mean efficiency in radon reduction was 92% (91% for houses with radon level 200-800 and 96% for houses with radon level

	above 800 Bq/m^3). They found the difference in efficiency related to the initial radon level (Long, Fenton, Cremin, & Morgan, 2013).
Norway	Homeowners of 12 houses who were part of an earlier study received remediation advice. A single contractor remediated nine homes by installing an internal sump, one by installing an external sump, one by ventilating the crawl-space under the house, and one house by installing a naturally ventilated sump and one by a fan mounted to increase the sub-slab depressurization. Ten years after these remediations, only 3 out of 12 houses showed radon concentrations under the action level of 200 Bq/m^3 (5.4 pCi/l). Mitigation by enhanced ventilation alone was not useful for houses with radon above the action level. Home-owners' behavior change to open windows more frequently was found unrealistic. The mitigation techniques involving a minimum physical change to a building, e.g. a radon sump, were generally better as they did not usually require an active role from the building's occupants after installation. Considering the long-term viability of radon remediation techniques, post-remediation radon testing is recommended at periodic intervals, preferably every five years (Rydock, Næss-Rolstad & Brunsell, 2002)
Sweden	Akbari & Oman (2013) examined the performance of the heat recovery ventilation system and energy saving by measuring and analyzing radon level and cost of heat exchange. They developed a multizone model of a detached house in IDA Indoor Climate and Energy lab (IDA ICE 4.0). The model measured energy use for heating, ventilation and total energy use. The dynamic simulation analysis showed that the heat recovery ventilation system was proved to reduce about 100% radon-level, and it saved 74% energy from ventilation loss amounted about 30 kWh.m2 per year. Life cycle cost analysis used for assessing total costs and the result showed that using this system is quite cost-effective and investment would pay back in 12 years.
Finland	Arvela (2001) tested 900 flats where >10% of them exceeded radon level 400 Bq/m^3. The interventions examined the effectiveness of SSDS, radon wells, sealing entry routes and installation of fresh air vents. The best mitigation with a combination of SSDS and radon wells found from 50 to 80% effectiveness. Sealing entry routes and the installation of fresh air vents led to radon reductions of 30-60% and 50% respectively. It was recommended that, on a case-by-case basis, installation of fresh-air vents and entry route sealing should be considered first. If these are proved inadequate, a combination of SSDS and radon well should be considered.
Belgium	Due to the underlying geology, southern Belgium is the high radon area. Typically, all dwellings with the slab directly on the slate had high radon concentrations with a constant radon entry rate. Paridaens, de Saint-Georges and Vanmarcke (2004)

	employed an active SSDS with a single extraction radial fan remediation and noted an initial radon reduction at a factor of 10. Then, run the fan at full speed and compared to a lower speed one; thus, proved how active fan can lower the pressure gradient across the slab. A survey by the Belgian Building Research Institute in collaboration with the University of Ghent tested several hundred houses. Based on the survey results, 2% or 160 homes found to have significant radon problems (radon level in living areas around 3000 Bq/m^3) and rigorously mitigated those houses by installing sub-floor ventilation system and noted up to 90% effectiveness.
Germany	Wang, Meisenberg, Chen, Karg and Tschiersch (2011) tested filtration techniques with HEPA filters and a simple surgical mask material for their potential to reduce the indoor exposure regarding the total effective dose for mixed radon and thoron indoor atmospheres. They performed the tests inside an experimental room creating stable conditions. In case of attached radon decay products, they noted a faster but weaker reduction in comparison to the thoron decay products (−70% vs −80% at a filtration rate of 0.5/h with a HEPA filter). These observed theoretical variations are attributed to their different nuclear half-lives. Researchers recommended a permanent filtration because of the slow decrease of the decay product concentrations.
Slovenia	The most frequent radon problems in Slovenia occur in dwellings constructed on clay ground with unventilated basements and non-insulated floors. Effective remediation has been achieved by adding a concrete layer to the basement floor, covering with a bitumen emulsion and a polyvinyl sheet and sealing all wall cracks. Insulation of the floor alone reduced radon concentrations by 20%. Passive ventilation of the cellar, utilizing ducts leading from the basement to the roof, gave a 10-fold reduction in radon during the winter (Jovanovic & Kanduc, 1994).
Hong Kong	Gao, Tang, Tam, and Gao (2008) conducted an experimental study to test anti-radon coating for mitigating indoor radon concentration in a newly constructed building. Under the experimental condition, the maximum and average hourly background radon concentrations were recorded at 130,000 and 100,000 Bq/m^3 respectively. The effectiveness of reducing indoor radon was up to 99.85% in 72 hours.
Czech Republic	Experiments by Martin and Jirı (2001) from the Czech Technical University in Prague with moisture-proof insulation over the entire surface of the floors and basement walls in contact with the soil showed effectiveness in reducing radon in new buildings. This approach depends on building and soil characteristics aimed to identify the minimal thickness of radon-proof membranes. They set following criteria for the insulation: a) It endures the expected lifetime of the building as a maintenance is impractical and expensive. b) It resists damages by microbiological chemical

	agents. c) It sustains movements of the building sub-structure. d) It is less sensitive to piercing. e) It is complete with extra gears for the external and internal corners, edges and pipe entries to ensure higher quality and air-tightness. f) It is site and weather resistant. g) It prevents diffusion and convective flow of soil gas containing radon.
Switzerland	Roserens and Jungck (1994) identified the most successful method in Switzerland to be the forced air exchange to mitigate medium to high radon levels. This applies small overpressure by sealing the basement to prevent air infiltration from the soil.
Italy	Tunno et al. (2017) applied SSDS with active ventilation to reduce radon below the action level (500 Bq/m^3). They noted from 75% to 95% effectiveness of the system. They also explored some critical aspects related to the karstic nature of the area, optimization of remediation, and architectural issues related the historical interest.
Spain	Vázquez et al. (2011) examined sump effectiveness at model houses in Spain where the average radon level at a 1m deep was 250 kBq/m^3. They evaluated it in two locations: underneath the basement, which involved cutting openings into the foundation, ground floor and roof slabs, and digging a pit outside the building exterior. The effectiveness of both sumps was equally tested with active and passive ventilation. The active system (with the wind speeds of over 8 m/s) was highly efficient to reduce radon levels by 91-99%, whereas the passive system reduced radon by 53-55%. At, however, passive ventilation across an external sump lowered radon levels by 95% due to a Venturi effect induced drop in pressure.
Austria	Huber et al. (2001) examined five different remedial methods to determine their efficiency for unusually high indoor radon concentrations (up to 274,000 Bq/m^3) in western Austria. A charcoal liquid scintillation with Alpha-Guard measured indoor radon concentration. The mitigation systems were as follows: House 1: A mechanical intake and outlet ventilation system with a heat exchanger in the basement, combined with a soil depressurization system for long-term stability. In the most favorable basement air pressure (1100 Pa), mean radon level dropped from 200,000 Bq/m^3 to 3,000 Bq/m^3 in 5 years. House 2: SSDS with two active fans to draw radon from the sub-flor area and soil below the part of house with no basement proved most effective till six years after mitigation. Then, micro-cracks appeared in the basement leading to high radon level required further sealing. House 3: A multilayer floor construction with a fan was used to suck radon from a layer between the bottom slab and floor. This reduced winter mean radon level from 25,000 Bq/m^3 to 1,200 Bq/m^3, with the fan on and the basement door closed.

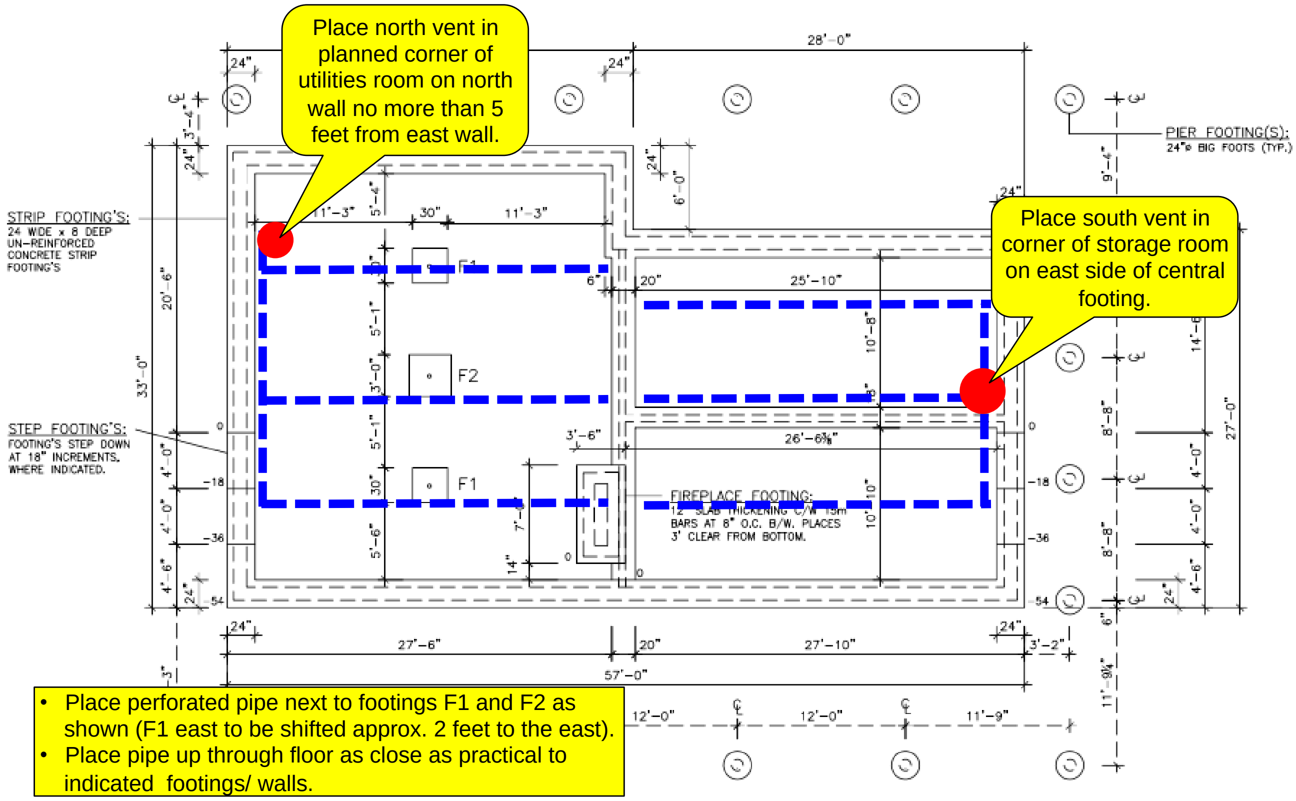
	House 4: A basement sealing (with a special silicate solution and a cement suspension) technique was unsuccessful with almost identical radon concentrations during all the five years since mitigation had started. House 5: A waterproof basement membrane in new homes reduced mean basement and ground floor radon concentration below 300 Bq/m^3 and 200 Bq/m^3 (action level). These interventions suggest that in high radon areas, mitigation plan should consider individual house wise plan that can provide sustained radon reduction over time. During the same year, Maringer et al. (2001) measured radon in five buildings in Upper Austria and a radon test house in the Austrian Research Centers with both active and passive radon detectors. Average radon level varied from 150 to 900 Bq/m^3 depending on location and seasons. They mitigated two high radon activity farmhouses with active SSDS, and a single-family house with passive sub-floor ventilation system. The effectiveness noted was 90% and 50% respectively.
Japan	In Japan, two types of air cleaners used: a) HEPA-filter and b) HEPA with a deodorizing activated carbon-filter to measure effectiveness regarding the reduction of radon equilibrium equivalent concentration (EEC). EEC was found significantly ($p < 0.01$) lower with both the filters compared to the control houses (Yasuoka, Ishikawa, Tokonami, Takahashi, Sorimachi, & Shinogi, 2009).

Appendix 30. Sub-slab depressurization system installed in a Canadian new house (a-g)

Le Chateau:

a. An old family house at the outskirts of Ottawa with radon level over 600 Bq/m^3 was planned to remediate while renovating/building. The owner, a participant of our qualitative study (SP16), installed sub-slab depressurization system along with sealing and barrier membrane. Due written permission received for publishing these seven (a-g) photos and/or designs.

b. Floor plan with point (red) of radon gas venting layout



c. Placing of sub-slab perforated pipes during construction

d. Basement membrane placing and sealing of floors

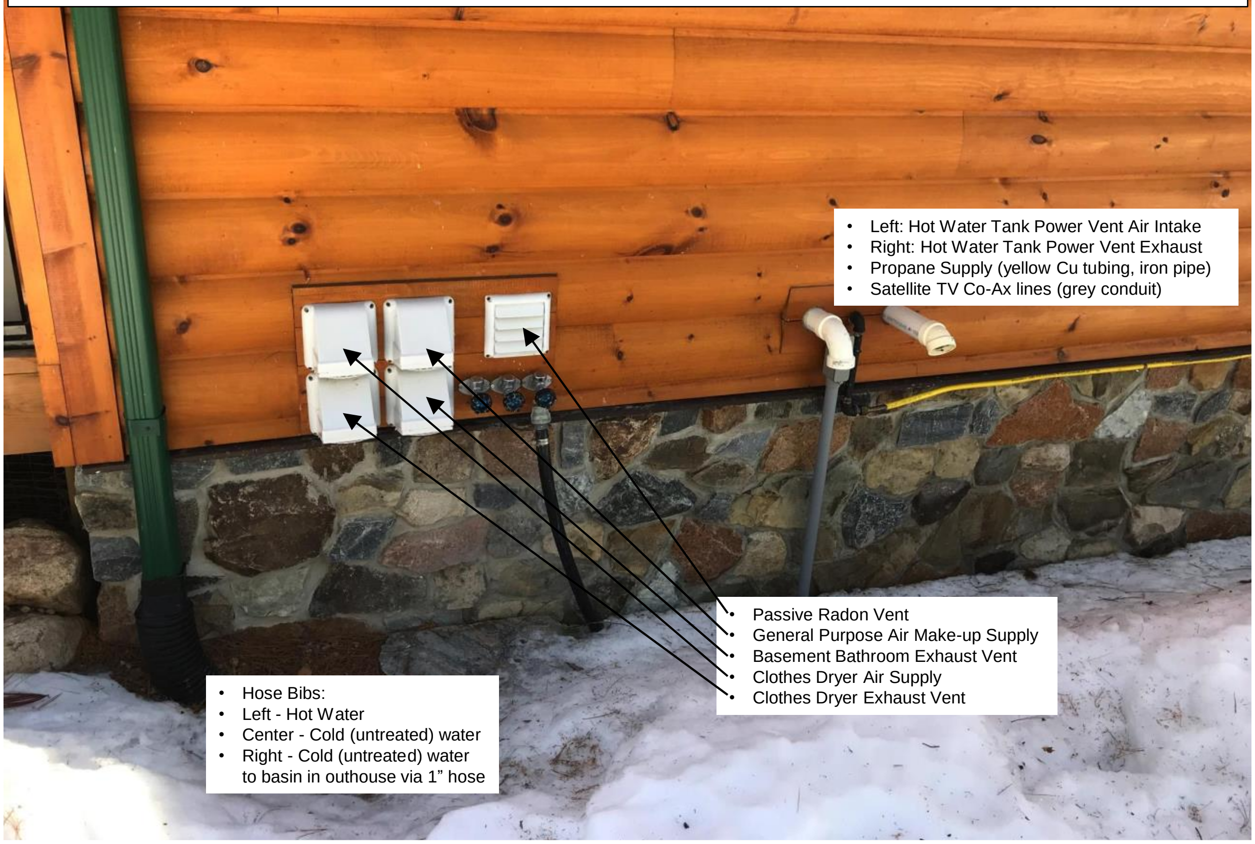
e. SDSS after installation (inside)

Passive radon vented from under basement floor to exterior: two vents were installed, one each at south and north ends This is north one in utility room.

Also visible but not relevant to radon mitigation:
- Hot Water Heater
- Water Softener
- Switch & relay for shore well water pump (above)
- SaniFlo pump for basement bathroom
- Open pipe to shore well for water line, power cable for water pump (230 volt), power cable for water line and shore well heater (115 volt), low voltage cable for shore well water level gauge (12 volt)
- Radon vent
- Pressure tanks for water system (lower: softened but not purified water, upper: softened and purified water)

Also visible:
- Insulated duct for general purpose air make up with loop to minimize unneeded air flow
- top left corner: bathroom exhaust duct
- PEX lines to hose bibs
- PEX lines to and from water softener
- Plumbing vents
- Sump

f. Outdoor vents after installation



g. Real-time radon measurement showing level after mitigation

Radon level readings taken 2019 03 26 showing results from house being mostly closed up during winter. House is recent construction tightly sealed per current building code. Summer readings were about 50% lower.