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RESIDENTIAL RADON EXPOSURE, ITS CONTRIBUTION TO LUNG CANCER, AND SOCIAL DETERMINANTS OF RADON TESTING

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RESIDENTIAL RADON EXPOSURE, ITS CONTRIBUTION TO LUNG CANCER, AND SOCIAL DETERMINANTS OF RADON TESTING

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Nursing
at the University of Kentucky

By
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Lexington, Kentucky

Director: Dr. Ellen J. Hahn, Professor of Nursing

Lexington, Kentucky

2020

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ABSTRACT OF DISSERTATION

RESIDENTIAL RADON EXPOSURE, ITS CONTRIBUTION TO LUNG CANCER, AND SOCIAL DETERMINANTS OF RADON TESTING

Lung cancer is a highly preventable form of cancer. Cigarette smoking is the leading cause of lung cancer followed by radon gas exposure and exposure to secondhand smoke. Kentucky leads the nation in both incidence and mortality from lung cancer. Tobacco use in Kentucky continues to be a major public health concern as nearly one-quarter of adults report current tobacco use and just over one-third of Kentucky homes with children lack rules which prohibit smoking in the home. Radon, a colorless, odorless radioactive gas, occurs naturally from the decay of uranium found in rocks and soil and is harmful when it gets trapped indoors. When inhaled, the radioactive particles deposit in the lungs, irradiating cells in the airways. Indoor radon exposure is a cause of lung cancer among smokers and non-smokers; however, a synergistic effect exists between tobacco smoke exposure and radon on the development of lung cancer, putting those who smoke or are exposed to tobacco smoke at a 10-fold greater risk of developing lung cancer than non-smokers and those not exposed to secondhand smoke. Widespread use of tobacco is likely to blame for the high incidence of lung cancer in Kentucky; however, less is known about the contribution that radon exposure has on lung cancer incidence. Testing one's home for radon is a primary prevention strategy and is necessary to determine exposure risk. Despite public awareness of radon, the proportion of households that have completed home radon testing remains low, ranging from 3-15% of those surveyed. From a public health perspective, it is important to identify variables associated with completion of home radon testing and address disparities in testing in order to create healthy home environments for all. Particularly given the synergistic effect of tobacco and radon, identifying predictors of home radon testing could be useful for prioritizing the allocation of resources and the development of public policy to address environmental risk and improve the health of Kentuckians. The purpose of the dissertation is to: 1) review the literature on methods utilized to quantify population attributable risk (PAR) of residential radon exposure on the development of lung cancer; 2) explore predictors of home radon testing in rural Appalachia; and 3) examine the association between county-level social determinants of health and environmental exposures and rates of home radon testing.

This dissertation has three components; a systematic review of the literature, a prospective study of Appalachian residents, and a secondary analysis of state radon and

other population-level data. First, a search of published literature on attributable risk for radon-induced lung cancer was conducted using PubMed for all relevant studies published in English between 2008 and 2018 using the key phrases *radon AND attributable risk; lung cancer AND attributable risk; radon AND attributable fraction; lung AND attributable fraction; radon AND population attributable risk.* Second, using the Teachable Moment Model (McBride et al., 2003) as a theoretical framework, an exploratory, prospective study design was utilized to examine the association between the Teachable Moment Model constructs and home radon testing in a small sample of rural Appalachia residents. A convenience sample of 58 adult participants was recruited from two rural primary care clinics located in Appalachia Kentucky and were surveyed using a brief paper-and-pencil survey and given a free long-term home radon test kit. Binary logistic regression was used to examine the association between personal risk perception, emotional response, synergistic risk perception and home radon testing. Third, an ecological, descriptive study design was used to conduct a secondary data analysis of 54,683 observed radon values from Kentucky homes. Data from 1995-2016 were obtained from a statewide radon database. Multivariate linear regression was used to examine the association between county-level social determinants of health (e.g., median household income, median home value, percent living below poverty level, percent of the population over the age of 25 with at least a high school diploma, percent owner-occupied housing, and rural-urban status) and environmental exposures (e.g., radon exposure risk potential, adult smoking prevalence, and lung cancer incidence rates) and rates of home radon testing.

Results from the review of the literature revealed four models of excess relative risk typically used to estimate population attributable risk (PAR) associated with indoor radon exposure are described, including those proposed by the Environmental Protection Agency (EPA), the BEIR-VI exposure-age-concentration (EAC) model, the BEIR-VI exposure-age-duration (EAD) model, and the European Pooling Study model. Equations used to calculate PAR vary. Application of the EAC model resulted in higher estimates of PAR. PAR percentages ranged from 5-28% and total number of lung cancer deaths attributable to residential radon exposure ranged from 231-3,366 annually, with more radon attributable lung cancer deaths occurring among those with a history of smoking. When researchers hypothetically reduced radon exposure concentrations in the population, a reduction in radon-induced lung cancer mortality was noted. Uncertainties in estimations stem from differences in approximation of indoor radon concentrations and from use of the two BEIR-VI models since they extrapolate results from the studies of miners to assess lung cancer risk in the general population. Second, results from the prospective study showed that 28 of the 58 (48%) home radon test kits distributed in rural Appalachia were returned for analysis. Eight (29%) exceeded the EPA action level, three of which reported the presence of smoking in the home. Older adults were more likely to complete home radon testing (M= 51, *SD*= 11 years versus M= 41, *SD*= 16 years, respectively; $p = .008$). There were no differences in personal risk perception of lung cancer, lung cancer worry, or synergistic risk perception between those who completed home radon testing and those who did not. Many participants reported low perceived personal risk for lung cancer at baseline despite the fact that 29% of those who tested had high home radon levels. The multiple logistic regression model to determine demographic and personal characteristics predictive of testing status was significant

overall, with age as the only significant predictor. Age was associated with completion of radon testing. For every 5-year increase in age, participants were 47% more likely to test their homes for radon. Third, results from the secondary analysis revealed that the average county-level aggregate annual residential testing rate in Kentucky was 13.4 per 10,000 households. Multiple linear regression model to assess predictors of county-level residential radon testing rates was significant overall, with county-level median home value, rural-urban status, upper quartile of the distribution of radon values, and adult smoking prevalence making statistically significant unique contributions to the prediction of residential radon testing rates. For each $10,000 increase in median home values, there was a corresponding increase of 1.54 in the annual rate of residential radon testing per 10,000 households. For every 1-unit increase in RUC value (i.e., an increase in county-level rurality), the rate of annual testing per 10,000 households increased by 1.95. For each additional 1 pCi/L of radon exposure risk potential at the county level, annual rates of residential radon testing increased by 1.36 per 10,000 households. Finally, for each 1% increase in county-level adult smoking prevalence, annual rates of residential radon testing per 10,000 households decreased by 0.50.

Studies to determine attributable risk of radon-induced lung cancer vary in methodology. Given the uncertainties associated with extrapolation of results from miners to the general public, as per the BEIR-VI EAC and EAD models, additional well designed case-control studies using residential radon measurements are needed to provide further evidence for the use of residential radon models over models developed from studies of miners. Providing free home radon test kits as a cue to action in the primary care setting shows promise in prompting radon testing in Appalachia. As radon-induced lung cancer risk increases with exposure over time, efforts are warranted to encourage home radon testing among younger individuals. Additionally, counties with low median home values and high prevalence of adult smoking may benefit the most from public health interventions to increase home radon testing. Public health strategies focused on reducing tobacco and radon exposure in the home are needed in order to reduce the burden of lung cancer and create healthy home environments for all.

KEYWORDS: Radon, Lung Cancer, Teachable Moment, Attributable Risk, Primary Prevention, Social Determinants

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RESIDENTIAL RADON EXPOSURE, ITS CONTRIBUTION TO LUNG CANCER, AND SOCIAL DETERMINANTS OF RADON TESTING

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DEDICATION

This dissertation is dedicated to my husband Derrick and our children Tegan, Josie and Piper. You are my greatest inspiration. Thank you for your unwavering love and support.

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"*Trust in the Lord with all your heart and lean not on your own understanding; in all your ways submit to him, and he will make your paths straight."* *Proverb 3:5-6*

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CHAPTER 1:

INTRODUCTION

1.1. Background

The American Cancer Society estimates 228,820 new cases and an estimated 135,720 deaths from lung cancer in 2020, yet the disease remains highly preventable (American Cancer Society [ACS], 2020). First-hand tobacco use is the number one cause of lung cancer followed by exposure to radon gas and secondhand smoke (SHS) (ACS, 2020). Radon is a colorless, odorless radioactive gas that occurs naturally from the decay of uranium found in rocks and soil. When inhaled, the radioactive gas and its progeny deposit in the lungs, irradiating cells in the airways (Environmental Protection Agency [EPA], 2016a). Each year approximately 15,400-21,800 lung cancer deaths are induced by radon exposure in the U.S., with approximately 2,900 of those occurring in individuals who have never smoked tobacco (National Research Council Committee on Health Risks of Exposure to Radon [NRC], 1999). While radon exposure is a cause of lung cancer among smokers and non-smokers, a synergistic effect exists between tobacco smoke exposure and radon on the development of lung cancer. Those who are exposed to tobacco smoke and are exposed to radon have a 10-fold greater risk of developing lung cancer than non-smokers (EPA, 2019). For example, when exposed to 4 picocuries per liter of air (pCi/L) of radon over a lifetime, 62 per 1,000 smokers would develop lung cancer versus 7 of 1,000 never smokers (EPA, 2019). Furthermore, lung cancer risk increases with longer duration and higher concentration of radon exposure (NRC, 1999).

Radon is present in outdoor and indoor air in varying concentrations. The Environmental Protection Agency (EPA) estimates that the average outdoor radon

concentration in the U.S is 0.4 pCi/L, while indoor concentrations average 1.3 pCi/L (EPA, 2016a). Human exposure to radon is largely due to high concentrations in the home, where Americans spend the majority of their time and where the radioactive particles enter and become trapped (EPA, 2016a). The EPA has estimated that one in every 15 homes in the United States has a high radon level (EPA, 2016a). While there is no safe level of radon exposure, the U.S. Surgeon General advises all Americans to test indoor radon levels in their homes to determine their exposure risk (United States Department of Health and Human Services, 2005). Additionally, the *World Health Organization Housing and Health Guidelines* (2018) offer evidence-based recommendations for creating healthy home environments, including addressing elevated radon exposure in homes through the promotion of home radon testing.

Various devices exist to measure the concentration of radon in the air. Devices are classified as either equilibrating, integrating, or continuous (American Association of Radon Scientists and Technologists [AARST], 2013). In addition, devices are often described in terms of duration of measurement, i.e., short-term, long-term, continuous, and grab, as well as either passive or active (World Health Organization [WHO], 2009). Short-term devices are deployed for 2-90 days; long-term devices for 91-365 days; continuous measurement is ongoing and can provide levels of measurement within as little as one hour or less; and grab samples provide real time alpha particle counts within 6 minutes (RadonAway, 2018; WHO, 2009). While short-term measurement and grab sample devices provide an initial indication of the mean long-term radon concentration in a home, the short period of measurement does not account for daily and seasonal variation in radon concentration. Therefore, long-term measurement of radon

concentration is the preferred method for most accurately estimating radon exposure and when making decisions about mitigation (WHO, 2009). Testing a home for radon can be done by the homeowner, or by a certified radon professional. For homeowners who seek to test themselves, home radon test kits can often be obtained from home improvement stores, local health departments, and state radon programs. Otherwise, homeowners are encouraged to contact their state radon program for a list of certified radon measurement and mitigation professionals.

Despite public awareness, the proportion of people who have completed home radon testing remains low, ranging from 3-15% of those surveyed (Eheman et al., 1996; Wang et al., 2000). Multiple factors that contribute to home radon testing include: higher income (Halpern & Warner, 1994; Hill et al., 2006; Nissen et al., 2012; Zahnd et al., 2017); higher education (Halpern & Warner, 1994; Nissen et al., 2012; Butler et al., 2018; Zahnd et al., 2017); urbanicity (Zahnd et al., 2017); younger age (Halpern & Warner, 1994; Wang et al., 2000); female sex (Halpern & Warner, 1994); home ownership (Hill et al., 2006); presence of children in the home (DiPofi et al., 2001); health concerns (Nissen et al., 2012; Rinker et al., 2014); knowledge of radon (Duckworth et al., 2002; Wang et al., 2000); perceived community radon risk (Weinstein et al., 1991); living in a high-risk radon zone (Wang et al., 2000; Zahnd et al., 2017); perceived severity (Duckworth et al., 2002: Weinstein et al., 1991); perceived susceptibility and social influence (Duckworth et al., 2002; Rinker et al., 2014; Weinstein et al., 1991); availability of free or discounted testing kits (Nissen et al., 2012; Butler et al., 2018); discussion with a real estate agent (Neri et al., 2018); and physician recommendation (Nissen et al., 2012).

The U.S. Surgeon General and the EPA have suggested homeowners take action to lower the risk of radon-induced lung cancer when the radon level in their home is $\geq$ 4.0 pCi/L (EPA, 2016a; United States Department of Health and Human Services, 2005). Various radon reduction methods exist; however, the recommended method used to reduce radon levels in homes is soil suction, or radon mitigation systems. These systems work by using a fan to draw radon from below the home and vent it through a pipe to the outside air above the home where it is quickly diluted. Installation of these systems can reduce the radon level in a home by up to 99% (EPA, 2016b). The EPA encourages the public to contact a certified radon mitigation contractor for system installation. Many states, including Kentucky, require radon professionals be licensed, certified, or registered through their state radon program (EPA, 2016b). The cost of radon mitigation varies depending on the radon reduction method employed, and the size, foundation type, and design of the home (EPA, 2016b). While the EPA suggests that mitigating a home costs "about the same as other common home repairs," the actual expense can vary from $1250-$3000 (EPA, 2016a, p. 9; Hahn et al., 2014).

The American Cancer Society estimates that in 2020, Kentucky will have more new cases and deaths from lung cancer than any other cancer (ACS, 2020). Widespread use of tobacco is to blame for the high incidence of lung cancer, as 24.6 % of adults in Kentucky are current smokers (Department for Public Health, Cabinet for Health and Family Services, 2018) and many Kentuckians are exposed to SHS in their homes (King et al., 2013), workplace, and in public places (Kentucky Center for Smoke Free Policy, 2019). Although radon is the second leading cause of lung cancer, little is known about the specific contribution that radon exposure has on lung cancer incidence in Kentucky.

Testing one's home for radon is necessary to determine exposure risk, yet it is estimated that fewer than 1% of homeowners complete radon testing every year in Kentucky (Radon Policy Division, unpubl. data). From a public health perspective, it is important to know the proportion of cases in a total population that can be attributed to a known risk factor. Particularly given the synergistic effect of tobacco and radon exposure, estimating the burden of disease caused by residential radon exposure and identifying predictors of home radon testing could be useful for prioritizing the allocation of resources and the development of public policy to reduce environmental risks, save healthcare costs, and improve public health.

The purpose of the dissertation is to: 1) review the literature on methods utilized to quantify population attributable risk (PAR) of residential radon exposure on the development of lung cancer; 2) explore predictors of home radon testing in rural Appalachia; and 3) examine the association between county-level social determinants of health and environmental exposures and rates of home radon testing. This dissertation is comprised of three manuscripts, one addressing each study purpose and they are presented in Chapters Two through Four.

1.2. Summary of Theoretical Model

Primary care providers play an important role in the health of populations through the promotion of healthy behaviors to reduce risk of disease. Health events, such as healthcare visits and hospitalizations, are thought to be prime opportunities for teachable moments as they often raise an individual's motivation for behavior change. As such, the Teachable Moment Model (TMM) was selected as the theoretical framework for this dissertation (Figure 1.1) (McBride et al., 2003). The TMM has been used to guide

research on individual health behavior change and theorizes that health events (e.g., receiving a free radon test kit at a healthcare visit) prompt individuals to subjectively evaluate the significance, cause and meaning of the event (McBride et al., 2008). The three key constructs of the TMM include: (1) perception of personal risk and outcome expectancies; (2) affective or emotional response; and (3) health-related self-concept. When a health event is significant enough, these three constructs create a cognitive response, which results in increased motivation, skill acquisition and self-efficacy, leading to behavior change (McBride et al., 2003). McBride et al. (2003) suggests that having an understanding of how a health event affects each of the three constructs is important to understanding the potential for a teachable moment and the development of interventions which can promote healthy behavior change. Research using the TMM can be complicated due to the unpredictable nature of health events. However, the TMM has been applied as a theory to guide the understanding of health behavior change such as colorectal cancer risk reduction (McBride et al., 2008), lung cancer risk reduction (Butler et al., 2017; Hahn et al., 2014b; Hahn et al., 2017), smoking cessation (Kells et al., 2013), gestational diabetes mellitus treatment (Okely et al., 2019), and diet and physical activity during pregnancy (Atkinson et al., 2016). The TMM in this study was used to provide insight into how teachable moments can promote residential radon testing in Appalachia Kentucky, adding to the body of literature on radon risk reduction to prevent lung cancer.

1.3. Overview of the Chapters 2-4

1.3.1 Overview of Chapter Two

The first manuscript is a systematic review of the literature to: a) examine the studies that have assessed the proportion of lung cancer that can be attributed to

residential radon exposure, taking into account tobacco and radon exposure and stratifying by smoking status; and b) explore the methods utilized to quantify population attributable risk (PAR) for radon-induced lung cancer. The systematic review revealed that the methods used to determine PAR for radon-induced lung cancer vary, with the most common utilizing the excess relative risk estimates from the European Pooling Study Model (Darby et al., 2005), the BEIR-VI exposure-age-duration and exposure-age-concentration models (NRC, 1999), and the Environmental Protection Agency models (EPA, 2003). Equations used to calculate population attributable risk also vary. Regardless of the methods used, exposure to residential radon demonstrates an increased risk for lung cancer, particularly among ever-smokers, and is a public health concern. Reduction of home radon levels through radon mitigation has the potential to save lives. Quantification of radon induced lung cancers within each state may be useful to public health officials and state radon programs and can be used to guide public policies aimed at reducing radon exposure.

1.3.2 Overview of Chapter Three

The Teachable Moment Model (McBride et al., 2003) was used to guide this exploratory, prospective study, offering free radon test kits at two primary care offices in rural Appalachia Kentucky to serve as a cue to action to: 1) compare differences in sociodemographic characteristics, personal risk perception of lung cancer, lung cancer worry, and synergistic risk perception among rural Appalachia residents who completed home radon testing with those who did not, after receiving a free long-term test kit at a rural primary care clinic; and 2) examine the association between the Teachable Moment Model constructs of personal risk perception, emotional response, and synergistic risk perception and home radon testing in a small sample of rural Appalachian residents.

Findings from this study revealed that providing free home radon test kits as a cue to action in the primary care setting shows promise in prompting home radon testing in Appalachia. Many participants reported low personal risk perception for lung cancer despite 29% of those who tested having home radon levels at or above the Environmental Protection Agency recommended action level of 4 pCi/L. There were no differences in personal risk perception of lung cancer, lung cancer worry, or synergistic risk perception between those who completed home radon testing and those who did not. The multiple logistic regression to determine demographic and personal characteristics predictive of testing status was significant overall, with age as the only significant predictor. For every 5-year increase in age, participants were 47% more likely to complete home radon testing.

1.3.3 Overview of Chapter Four

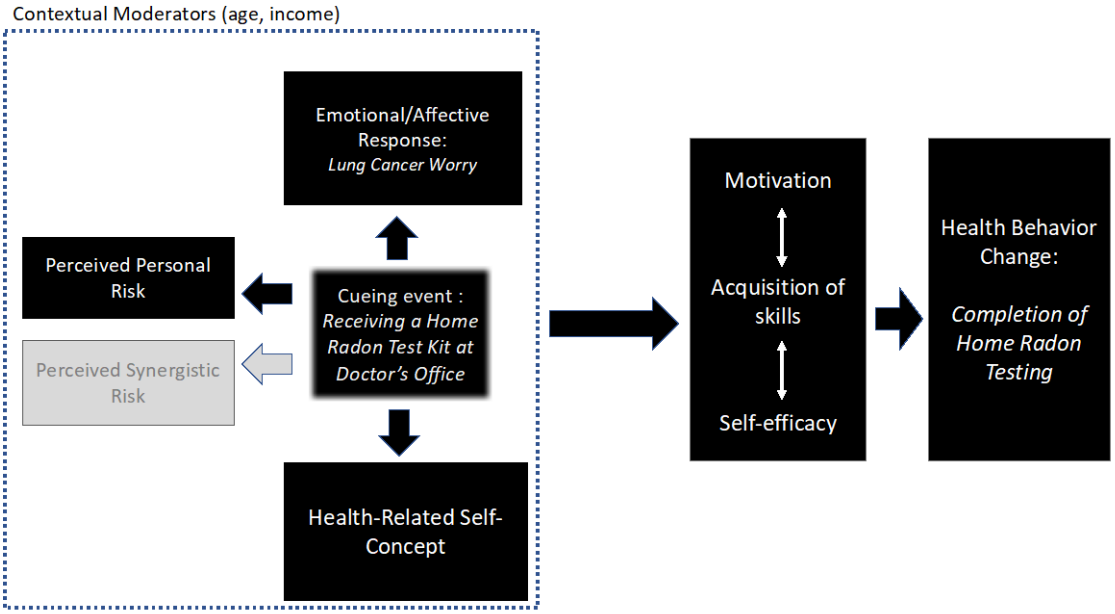
As people spend the majority of their lives inside their home, addressing environmental exposures in the home is a public health priority. Testing one's home for radon is a primary prevention strategy for the prevention of lung cancer, yet disparities in home radon testing exist. The primary aim of this study was to examine the association between county-level social determinants of health (e.g., median household income, median home value, percent living below poverty level, percent of the population with at least a high school diploma, percent owner-occupied housing, and rural-urban status) and environmental exposures (e.g., radon exposure risk potential, adult smoking prevalence, and lung cancer incidence rates) and rates of home radon testing. An ecological, descriptive study design was used to conduct a secondary data analysis of 54,683 observed radon values from Kentucky homes. Data from 1995-2016 were obtained from a statewide radon database. Median home value, rural-urban status, upper quartile of the

distribution of radon values, and adult smoking prevalence each made statistically significant unique contributions to the prediction of home radon testing rates. For each $10,000 increase in median home values, there was a corresponding increase of 1.54 in the annual rate of residential radon testing per 10,000 households. For every 1-unit increase in RUC value (i.e., an increase in county-level rurality), the rate of annual testing per 10,000 households increased by 1.95. For each additional 1 pCi/L of radon exposure risk potential at the county level, annual rates of residential radon testing increased by 1.36 per 10,000 households. Finally, for each 1% increase in county-level adult smoking prevalence, annual rates of residential radon testing per 10,000 households decreased by 0.50.

In summary, this dissertation aimed to add to the body of research involving attributable risk of radon-induced lung cancer and residential radon testing as a means of lung cancer prevention. Findings from this dissertation can be used to inform healthcare providers, public health officials, and lawmakers on the potential dangers of radon exposure, particularly among those also exposed to tobacco smoke, as well as individual and population-level predictors of home radon testing. Such information can be used to guide public health initiatives which aim to increase radon testing and mitigation and subsequently reduce the burden of lung cancer.

Figure 1.1

Heuristic Model for Teachable Moments



Note. Adapted from McBride et al., 2003. Original constructs are in black.

CHAPTER 2:

ATTRIBUTABLE RISK OF RADON-INDUCED LUNG CANCER: A SYSTEMATIC REVIEW

2.1. Background

Radon is a colorless, odorless radioactive gas released from the natural decay of uranium found in rocks and soil. In 1988, the International Agency for Research on Cancer classified radon as a group 1 carcinogen after evaluating evidence of carcinogenicity of radon exposure and its decay products in animal and human studies (World Health Organization [WHO], 1998). Evidence cited by the International Agency for Research on Cancer (WHO, 1998) suggested that radon is a cause of the development of lung cancer; as radon and its short-lived progeny are inhaled, radioactive alpha particles are deposited along the respiratory tract, irradiating the cells in the airways and increasing the risk of lung cancer (Environmental Protection Agency [EPA], 2016).

In 2020, lung cancer is projected to be the leading cause of cancer mortality in both men and women in the United States (American Cancer Society [ACS], 2020). The American Cancer Society estimates that there will be 228,820 new cases and 135,720 deaths from lung cancer in 2020, yet the disease remains highly preventable (ACS, 2020). Tobacco use is the number one cause of lung cancer followed by exposure to radon gas and secondhand smoke (SHS) (ACS, 2020). In the United States, concentration of radon gas is measured in picocuries per liter (pCi/L). More commonly seen throughout the world, radon concentration is measured using the International System of Units (SI) measure of Becquerel per cubic meter of air (Bq/m^3). In comparison, 1.0 pCi/L is equal to 37 Bq/m^3. The average outdoor annual radon concentration throughout the world varies between 0.1-10 Bq/m^3 (0.003 – 0.27 pCi/L), while indoor radon concentrations vary

between approximately 3 Bq/m^3 to greater than 160 Bq/m^3 (0.08 - >4.32 pCi/L) (WHO, 1998). Radon concentrations are found to be higher indoors as the gas accumulates and is trapped after entering through cracks in walls, basement floors, and foundations (EPA, 2016). While radon is present in both indoor and outdoor air, human exposure to radon is largely in the home, where individuals spend the majority of their time.

Radon exposure as a cause of lung cancer was first suspected in the twentieth century (WHO, 2009); and studies of underground miners and residential case-control studies have further provided supporting evidence. In 1999, the National Research Council (NRC) Committee on Health Risks of Exposure to Radon released the Health Effects of Exposure to Radon BEIR VI report (National Research Council Committee on Health Risks of Exposure to Radon [NRC], 1999). In this report, the NRC committee provided evidence from 11 major cohort studies of underground miners to illustrate the risk of lung cancer mortality from radon exposure (NRC, 1999). Evidence suggested that in the United States, between 10% and 14% of all lung cancers are attributable to indoor radon exposure, accounting for approximately 15,400 – 21,800 cases per year, with approximately 2,100-2,900 cases occurring in never-smokers (NRC, 1999). Furthermore, evidence indicated a synergistic effect between tobacco and radon exposure, with more radon-induced lung cancers occurring in those with a history of smoking (NRC, 1999).

In recent years, pooled analyses of case-control residential studies in Europe, China, and North America have provided additional evidence of the dangers of radon exposure. Darby et al. (2005) combined data from 13 case-control studies conducted in nine different European countries to explore risk of lung cancer associated with residential radon exposure. In total, these studies examined data from 7,148 cases and

14,208 controls. Evidence from the combined analysis indicated an 8.4% (95% CI = 3.0%-15.8%) increase in the risk of lung cancer per 100 Bq/m^3 of observed radon. After correcting for random uncertainties in measuring radon concentrations, the risk increased to 16% (95% CI = 5%-31%) per 100 Bq/m^3 and the increase did not vary significantly by study, age, sex, or smoking history (Darby et al., 2005). Furthermore, the dose-response relationship appeared to be linear, with no threshold (Darby et al., 2005). Second, Lubin, et al. (2004) combined data from 2 case-control studies of residential radon conducted in Shenyang, China and the eastern Gansu province of China to explore risk of lung cancer from radon exposure. The pooled analysis included 1,050 cases and 1,996 controls. Evidence from the combined analysis indicated a 13% (95% CI = 1%-36%) increase in the risk of lung cancer per 100 Bq/m^3 (Lubin et al., 2004). Third, Krewski et al. (2006) combined primary data from seven case-control studies conducted in North America. The total analysis represented 4,081 cases and 5,281 controls. Evidence from this combined analysis indicated a 10% (95% CI = 0.01-0.26) increase in the risk of lung cancer per 100 Bq/m^3 increase in observed radon (Krewski et al., 2006).

Sufficient evidence from miner cohort and case-control residential studies globally asserts that radon exposure is a leading cause of lung cancer. In addition, evidence has demonstrated a synergistic effect of radon and tobacco smoke exposure, putting those who are exposed to radon and tobacco smoke at a higher risk of developing lung cancer (EPA, 2019). When exposed to 4.0 pCi/L of radon over a lifetime, it is estimated that 62 per 1,000 smokers would develop lung cancer versus 7 of 1,000 never smokers (EPA, 2019). While conventional tobacco use is declining in the United States (Wang et al., 2018), approximately 47 million adults continue to use some type of

tobacco product (Wang et al., 2018), and the EPA suggests that 1 of every 15 homes in the U.S. has an elevated radon level, placing many Americans at risk for radon-induced lung cancer (EPA, 2016).

Despite the risk, several studies have found that the proportion of Americans who have completed home radon testing remains low (Eheman et al., 1996; Wang et al., 2000). In addition, no federal policies currently mandate home radon testing, and testing remains voluntary in most states (Environmental Law Institute, 2018). While there is no safe level of tobacco or radon exposure, creating smoke-free homes and reducing the concentration of radon in homes to levels below the EPA's recommended action level of 4.0 pCi/L has the potential to reduce incidence and mortality from lung cancer.

Quantifying the impact of tobacco and radon exposure on morbidity and mortality at the population level, has the potential to guide policy development. In epidemiologic studies, 'attributable risk' refers to an estimate of the amount of risk that is accounted for by a given exposure and can be assessed by exploring risk among individuals as well as populations (Jekel et al., 2007). Population attributable fraction, meant to estimate the proportion of the disease risk in the total population associated with an exposure, was first proposed in 1953 by M.L. Levin (Levin, 1953). Since then phrases such as 'population attributable risk', 'population attributable risk proportion', 'excess fraction' and 'etiologic fraction' have been used interchangeably for the same concept (Rockhill et al., 1998). From a public health and prevention perspective, it is most helpful to know the proportion of cases in a total population that can be attributed to a risk factor. The relatively recent evidence from the pooled analyses of case-control residential studies conducted in Europe, China, and North America (Darby et al., 2005; Krewski et al.,

2006; Lubin et al., 2004) provide support for the determination of population attributable risk of radon-induced lung cancer using residential radon exposure and population-level data. Therefore, the purpose of this systematic literature review is to identify recent studies that have assessed the proportion of lung cancer that can be attributed to residential radon exposure, describe the variables and methods utilized to quantify attributable risk and number of radon-induced lung cancers, taking into account smoking status and sex, and examine the potential effects of radon mitigation on reductions in radon-induced lung cancer mortality.

2.2. Methodology

A search of current published literature on attributable risk for radon-induced lung cancer was conducted using PubMed for all relevant studies published in English between 2008 and September 2018. Literature prior to 2008 was not considered in order to capture recent literature following the release of the case-control residential study findings (Darby et al., 2005; Krewski et al., 2006; Lubin et al., 2004). The following key phrases were used in the search: *radon AND attributable risk; lung cancer AND attributable risk; radon AND attributable fraction; lung AND attributable fraction; radon AND population attributable risk.* Titles and abstracts were screened for inclusion, and those found eligible were obtained in full text format. Full articles were then screened for inclusion. The reference section of each article was also screened for additional relevant articles based on title and year of publication. When a potentially eligible article was identified, a journal search was undertaken to retrieve the full text article and screen for inclusion. To be eligible for review, articles needed to: a) be designed as a quantitative assessment of lung cancer risk from residential radon exposure;

b) contain data on source of residential radon testing; c) include data on smoking prevalence d) examine lung cancer incidence or lung cancer mortality as the health outcome; and e) document a calculation of lung cancer attributable to residential radon exposure.

2.3. Results

The PubMed search initially provided 624 records. After screening titles using the five eligibility criteria, the number dropped to 30 records. Four articles were then discarded after reviewing abstracts as they did not meet the eligibility criteria. The full text of the remaining 26 articles were examined. Two additional studies were identified through reference citation. After examining the study design and methods of each of the 28 articles, 19 studies were excluded as they did not meet the eligibility criteria. A total of nine studies were identified for inclusion in this review; one of the nine studies assessed risk in two different countries (Figure 2.1). Table 2.1 provides a summary of the articles by author and date of publication, and lists the risk model used for the calculation of excess relative risk of radon-induced lung cancer, variables used in the calculation of population attributable risk, and findings.

2.3.1 Study Design

Each of the nine studies utilized a descriptive epidemiologic design to determine the population attributable risk of radon-induced lung cancer. Phrases referring to the number of lung cancers attributable to radon varied between studies. One study used the phrase, ‘population attributable risk’ (Grundy et al., 2017); one used ‘attributable risk in a population’ (Bochicchio et al., 2013); one used ‘attributable risk’ (Chen et al., 2012); one used ‘population attributable risk percent’ (Peterson et al., 2013); three used ‘population

attributable fraction' (Ajrouche et al., 2018; Lee et al., 2015; Menzler et al., 2008); one used the term 'attributable fraction' (Veloso et al., 2011); while one simply used the term 'fraction' (Truta-Popa et al., 2010).

2.3.2 Geographic Representation

The majority of the studies identified were conducted in Europe, Italy (*n*=1) (Bochicchio et al., 2013); Portugal (*n*=1) (Veloso et al., 2012); Romania (*n*=1) (Truta-Popa et al., 2010); and France (*n*=1) (Ajrouche et al., 2018); with one study assessing risk in Germany and Switzerland (*n*=1) (Menzler et al., 2008). The remaining studies assess risk in Canada (*n*=3) (Chen et al., 2012; Grundy et al., 2017; Peterson et al., 2013), and Korea (*n*=1) (Lee et al., 2015). Four studies determined attributable risk for an entire country (Ajrouche et al., 2018; Bochicchio et al., 2013; Chen et al., 2012; Menzler et al., 2008), four assessed risk in a region or province (Grundy et al., 2017; Peterson et al., 2013; Truta-Popa et al., 2010; Veloso et al., 2012) and one determined attributable risk in all regions of the country, as well as the country as a whole (Lee et al., 2015).

2.3.3 Measures

All studies utilized lung cancer mortality as the outcome variable versus lung cancer incidence. Each study obtained lung cancer mortality data from a national database responsible for tracking mortality within the respective countries. Additionally, population size was obtained from census data collected in the respective countries.

Eight studies utilized radon concentration data from nationally representative surveys, while Truta-Popa et al. (2010) utilized observed radon measurements from a representative sample of 667 dwellings gathered in the summer and winter months in Transylvania, Romania. Five studies provided information on the method of radon measurement. Chen et al. (2012), Grundy et al. (2017), Peterson et al. (203), Truta-Popa

et al. (2010), and Veloso et al. (2012) utilized radon data from long-term alpha track radon detectors and measured homes for 1-3 months. Corrections for radon measurement uncertainties varied. All studies, except for those located in Canada and Portugal, corrected radon measurement values for seasonal variation. In Canada, all measurements were gathered in the fall/winter months from two consecutive years. In Portugal, measurements were gathered twice from each home when possible; data from the time of year when measurements were conducted were not reported. Additionally, the radon database utilized by Menzler et al. (2008) corrected radon values in Switzerland by adjusting for which floor of the home the radon measurement was obtained, and then averaged the values by the number of homes within the community; radon values in Germany were also averaged by the number of homes within the community. All studies determined population-weighted mean radon exposure using observed radon values and population size. Population-weighted mean indoor radon concentrations varied by country, region, and province. Despite the lack of seasonal correction, the lowest mean concentration of indoor radon was from the cross-Canada radon survey (42 Bq/m^3), while the highest mean radon concentration was located in the Stei area of Transylvania, Romania (232 Bq/m^3).

Smoking prevalence rates specific to the country, region or province were used by all studies except two (Truta-Popa et al., 2010; Veloso et al., 2011). In Transylvania, Romania, data on smoking history were only available for one of the five counties, so investigators applied the same smoking prevalence to all counties included in the study (Truta-Popa et al., 2010). Veloso et al. (2011) calculated two separate estimates of PAR for Portugal by considering two smoking scenarios. In the first scenario, estimates of the

proportion of lung cancer deaths attributable to tobacco were gathered from a previous cohort study conducted in Portugal. Investigators then assumed that lung cancer deaths attributable to tobacco, 85% in males and 21% in females, corresponded to a smoker population. The second scenario assumed that 95% and 90% of all lung cancer deaths in men and women, respectively, occur among smokers as suggested by BEIR-VI (Veloso et al., 2012).

2.3.4 Excess Relative Risk Models

Excess relative risk is the hazard associated with exposure to a certain radon level compared with the threat of persons exposed to a reference level (Bochicchio et al., 2013). Among the retrieved studies, risk models used to estimate excess relative risk associated with indoor radon exposure varied between and among studies. In fact, four different risk models were used in the nine studies reviewed: BEIR-VI exposure-age-concentration (EAC) (NRC, 1999), BEIR-VI exposure-age-duration (EAD) (NRC, 1999); the Environmental Protection Agency model (EPA, 2003), and the European Pooling Study model (Darby et al., 2005).

The BEIR-VI EAC and EAD models proposed by the National Research Council Committee on Health Risks of Exposure to Radon were initially derived from 11 large cohort studies of miners who were heavily exposed to radon as well as a meta-analysis of 8 case-control studies in the general population (NRC, 1999). EAC and EAD models represent the multiplicative increment in the excess lung cancer risk beyond background levels resulting from exposure to radon (NRC, 1999). The models take into account time since exposure (E) and attained age (A). Three time-since-exposure windows are used to account for the cumulative exposure to radon progeny. The BEIR-VI report states that the period of radon exposure most relevant to the risk of developing lung cancer is 30 years,

ending 5 years before diagnosis of lung cancer (NRC, 1999). Therefore, time since exposure is expressed as a weighted combination of three exposure windows, $w_{5\text{-}14}$ is the cumulative exposure received 5-14 years prior to the attained age, $w_{15\text{-}24}$ is the cumulative exposure received 15-24 years prior to the attained age, and w_{25+} is the exposure 25 or more years ago. The third variable included in the models can then be either average concentration of radon over the time of the exposure (C) or duration of exposure (D). The equation is as follows:

$$ERR = \beta(w_{5-14} + \theta_{15-24}\, w_{15-24} + \theta_{25+} + w_{25+})\phi_{age}\Upsilon_z$$

where β indicates the risk coefficient of the exposure-response relationship, w indicates the exposure windows, $w_{5\text{-}14}$, $w_{15\text{-}24}$, and w_{25+}, the parameter θ is the relative contributions to risk from exposures 15-24 years and 25+ years or more before the attained age, θ_{15-24} and θ_{25+}, where θ_{5-14} is equal to 1. Attained age is represented by ϕ_{age} , and Υ_z represents either exposure duration or concentration. As lung cancer risk differs according to smoking status, β is adjusted by a factor of 2 for ERR calculation among non-smokers and a factor of 0.9 among smokers (NRC, 1999). Two of the five studies which utilized a BEIR-VI model did so with the EAC model only (Grundy et al., 2017; Peterson et al., 2013). The other three studies utilized both EAC and EAD models (Lee et al., 2015; Menzler et al., 2008; Veloso et al., 2012), with two also including the European pooling study model as a comparator (Lee et al., 2015; Menzler et al., 2008).

In 2003, the EPA published the *EPA Assessment of Risks from Radon in Homes* report. Following the release of the BEIR-VI models in 1999, the EPA's Office of Radiation and Indoor Air reviewed the methodology used in the BEIR-VI report and recommended a revised risk assessment. The revised Environmental Protection Agency

model provides excess relative risk values midway between the EAC and EAD models (Chen et al., 2012). Similar to BEIR-VI models, the EPA model does not include an exposure window for the 5 years immediately prior to the date of lung cancer diagnosis. The equation is as follows:

$$ERR(a) = \beta W^{*} \phi_{age}{}^{(a)}$$

where *a* is age in years. The parameter β *(= 0.0634)* represents the slope of the exposure-risk relationship. For a given radon concentration, the total exposure W^{*}, is calculated as the time weighted summation of time-since-exposure windows, $(w_{5-14} + \theta_{15-24} w_{15-24} + \theta_{25+} w_{25+})$, where w represents the exposure window of 5-14, 15-24, and 25 years or more before attained age *a,* and θ_{15-24} is equal to 0.78 and θ_{25+} is equal to 0.51. The parameter $\phi_{age}{}^{(a)}$ represents the decrease of excess relative risk with increasing age (Chen, 2005). Chen et al. (2012) was the only study to utilize the EPA model.

The fourth model is the European Pooling Model and is derived from a pooled analysis of residential radon data from 13 European case-control studies conducted in 9 European countries in order to estimate relative risk due to residential radon exposure. The analysis revealed that the dose-response relationship between radon concentration and lung cancer was linear with no evidence of a threshold. After correcting for uncertainties in assessing residential radon concentrations, the estimated excess relative risk was 0.16 per 100 Bq/m^3 (95% CI 0.05-0.31), meaning that the risk of lung cancer from radon exposure increases by 16% per 100 Bq/m^3 of lifetime exposure. In addition, Darby et al. (2005) found the risk did not differ significantly with study, age, sex, or smoking status. This pooled analysis was the first large scale study to demonstrate that

exposure to residential radon contributes to an increased lung cancer risk in the general population. The equation is as follows:

$$ERR = (1 + \beta x)$$

where β indicates the proportionate increase in risk per unit increase in measured radon and x indicates the measured radon concentration (Darby et al., 2005). The European Pooling model considers the 5-34 years prior to diagnosis period of radon exposure to be most relevant to the risk of developing lung cancer. In the equation, x is the time-weighted average of the radon concentrations in all dwellings occupied over the past 5-34 years (Darby et al., 2005). Ajrouche et al. (2018), Bochicchio et al. (2013), Menzler et al. (2008), and Truta-Popa et al. (2010) utilized the European Pooling Model only to determine ERR in France, Italy, Switzerland, and Romania, respectively. Lee et al. (2015) and Menzler et al. (2008) used both the European Pooling Model and the BEIR-VI model as comparators in Korea and Germany, respectively.

With the exception of Menzler et al. (2008), each study utilized a theoretical radon concentration of 0 Bq/m^3 to calculate excess relative risk for unexposed populations. Menzler et al. (2008) calculated excess relative risk of the unexposed utilizing a baseline concentration of radon equal to concentrations that would naturally be found outdoors in the respective countries.

2.3.5 Quantification of Population Attributable Risk

In simplest terms, the population attributable risk is given by the following formula:

$$PAR = \frac{\mathrm{ERR}(x) - 1}{\mathrm{ERR}(x)}$$

where ERR*(x)* is the lung cancer excess relative risk of the exposed in the population of interest at the average radon concentration *x*. Population attributable risk percentages ranged from 5% in Germany (Menzler et al., 2008) to 28% in Portugal (Veloso et al., 2012). Percentages ranged between 12% (Menzler et al., 2008) and 28% (Lee et al., 2015; Veloso et al., 2012) in the studies utilizing the BEIR-VI models. Population attributable risk percentage was 16% in the one study which utilized the EPA Model (Chen et al., 2012). In studies utilizing the European Pooling model, percentages ranged between 5% (Menzler et al., 2008) and 17% (Truta-Popa et al., 2010).

In the studies which utilized both BEIR-VI models and those that incorporated the European Pooling Model, application of the EAC model resulted in higher estimates of population attributable risk than the EAD and European Pooling Model. In Portugal, when assuming 95% and 90% of all lung cancer deaths in men and women respectively occur in smokers, the resulting population attributable risk percent ranged from 18%-28%, with the higher estimate being associated with the EAC model when compared to the EAD model (Veloso et al., 2012). Similar results were found in Korea (Lee et al., 2015). Regardless of smoking status, exposure to residential radon was attributed to 13.5%-19.5% and 20.4%-28.2% of lung cancer deaths in males and females, respectively, with higher estimates resulting from the EAC model. In comparison, the population attributable percent was much lower at 8.3% for both males and females when utilizing the European Pooling Model (Lee et al., 2015). In Germany, regardless of smoking status, the population attributable percent was found to be 12.0%, 8.5%, and 5.0 % utilizing the EAC, EAD, and European Pooling Models, respectively (Menzler et al., 2008). The population attributable risk for all of Canada determined by Chen et al. (2012)

using the EPA model was 16%. This estimation was similar to that found in Alberta (16.6%) and Ontario (13.6%) which were determined using the BEIR-VI EAC model (Grundy et al., 2017; Peterson et al., 2013).

2.3.6 Lung Cancer Mortality Attributable to Radon Considering Smoking and Sex

Table 2.2 provides the number of lung cancer deaths attributable to residential radon exposure given the associated population attributable risk percent, excess relative risk estimation model, and mean indoor radon concentration by country. Switzerland had the least number of lung cancers attributable to residential radon with 231 deaths (Menzler et al., 2008). Excluding the study conducted by Lee et al. (2015) which reported lung cancer mortality over a 20-year time span, Italy had the highest total lung cancer mortality attributed to radon, with approximately 3,366 deaths annually (Bochicchio et al., 2013).

To determine the number of lung cancer deaths attributable to radon, six studies utilized an *N*-calculation (Ajrouche et al., 2018; Bochicchio et al., 2013; Lee et al., 2015; Menzler et al., 2008; Truta-Popa et al., 2010; Veloso et al., 2012). Ajrouche et al. (2018) and Bochicchio et al. (2013) determined the total number of lung cancers attributable to radon exposure by multiplying the PAR by the total number of lung cancer deaths occurring per year. The calculations were then repeated separately by sex. To take into account the effect of smoking, Ajrouche et al. (2018) and Bochicchio et al. (2013) calculated the number of lung cancers attributable to radon exposure separately by smoking status using the total number of lung cancer deaths attributable to radon and the proportion of current, former, and never smokers in the population, as well as the relative risk of lung cancer for each smoking status category. Menzler et al. (2008) determined

the total number of radon-induced lung cancer deaths in Switzerland and Germany similarly for ever- and never-smokers only. In France, Ajrouche et al. (2018) determined approximately 2,199 and 725 radon-attributable lung cancer deaths occur annually among men and women respectively, accounting for 9.6% of the total annual lung cancer deaths. When considering the combined effect of radon and smoking, 2,204 (75%) of radon-attributable lung cancer deaths occurred among current smokers, 574 (20%) among former smokers, and 146 (5%) among never-smokers (Ajrouche et al., 2018). In Italy, Bochicchio et al. (2013) determined 2,605 and 762 radon-attributable lung cancer deaths occur annually among men and women respectively, accounting for approximately 10% of the total annual lung cancer deaths. The combined effect of radon and smoking indicated a greater synergistic effect in males with 1,865 (72%) of radon-attributable lung cancer deaths in men occurring among current smokers, 619 (24%) among former smokers, and 121 (5%) among never-smokers, compared to 456 (60%), 96 (13%), and 211 (28%) among current, former and never-smoking females respectively (Bochicchio et al., 2013). Bochicchio et al. (2013) reported the difference is likely due to the different smoking habits in the populations. Using the European Pooling Model, Menzler et al. (2008) reported 231 and 1,896 radon-attributable lung cancer deaths annually, accounting for 8.3% and 5.0% of the total annual lung cancer deaths in Switzerland and Germany, respectively. Of those, approximately 218 (94%) and 1,737 (92%) radon-attributable lung cancer deaths occurred among smokers in the respective countries (Menzler et al., 2008). In both countries, a greater burden of radon attributable lung cancer was found among males.

Lee et al. (2015) and Veloso et al. (2012) determined the number of radon-induced lung cancer deaths by sex for each region of Korea and Portugal respectively. Investigators divided the total number of lung cancer deaths observed in each gender by the number of deaths attributed and not-attributed to tobacco use (i.e., 85% and 21% attributable to Portuguese male and female smokers; 94% and 32% attributable to Korean male and female smokers). Investigators then applied the excess relative risk estimate to those attributable to smoking to determine the number of deaths attributable to smoking and radon, and attributable to tobacco only; and to those not-attributed to tobacco use to determine the number of lung cancer deaths attributable to radon only, and attributable to other factors (i.e., atmospheric pollution or occupational exposure) for each sex. Veloso et al. (2012) repeated the calculation using a second scenario in which it was assumed that 95% and 90% of all lung cancer deaths occur in male and female smokers, respectively. In Korea and Portugal, the number of lung cancer deaths attributable to radon were greatest using the ERR calculated from the BEIR-VI EAC model. Among males, smoking alone produced the most lung cancer deaths, and radon alone the fewest (Lee et al., 2008; Veloso et al, 2012). Among females, "other factors" incurred the greatest number of lung cancer deaths, and the deaths attributable to smoking and radon the fewest (Lee et al., 2008; Veloso et al., 2012). The findings may be due to the small proportion of female smokers in the population, however other possibilities (e.g., secondhand smoke exposure, pollution) were not addressed further in the studies.

Truta-Popa et al. (2010) determined the number of radon-induced lung cancer deaths by sex for each of the five counties of Transylvania, Romania by taking into account the excess relative risk and the total average annual number of lung cancer deaths

in each county. Smoking prevalence for males and females was assumed to be similar across all counties. Findings revealed a total of 59 (7%) radon attributable lung cancer deaths annually among non-smokers, 472 (56%) among male smokers and 275 (35%) among female smokers (Truta-Popa et al., 2010).

To determine the number of lung cancer deaths attributable to radon in Canada, Chen et al. (2012) followed the assumption from BEIR-VI report that 95% of lung cancer deaths in males and 90% of lung cancer deaths in females are ever-smokers. Chen et al. (2012) multiplied the total lung cancer deaths by sex by 0.95 for males and 0.90 for females, by the population attributable risk for ever-smokers to determine radon-induced lung cancer deaths among ever-smokers; and the total lung cancer deaths by sex multiplied by 0.05 for men and 0.10 for women, by the population attributable risk for never-smokers to determine radon-induced lung cancer deaths among never-smokers. Grundy et al. (2017) and Peterson et al. (2013) performed a similar calculation; however, the assumption was that 10% and 7.5% of lung cancer is diagnosed in never smokers in the respective study population, regardless of gender. In each study, a greater number of radon-induced lung cancer deaths occurred annually among ever-smokers and those exposed to smoking and radon, than those exposed to radon only.

Grundy et al. (2017) was the only study which utilized the estimated population attributable risk associated with radon-induced lung cancer mortality to estimate radon-induced lung cancer incidence. Under the assumption that the risk of death from lung cancer is the same for cases that were and were not caused by radon exposure, the radon-induced lung cancer population attributable risk calculated using lung cancer mortality data approximated the measure obtained with data on lung cancer incidence (Grundy et

al., 2017). Population attributable risk estimates calculated using lung cancer mortality data were then applied to lung cancer incidence data to estimate the number of cases of lung cancer attributable to residential radon exposure in Alberta Canada. Ajrouche et al. (2018) considered the use of lung cancer incidence data but reported that incidence data were not available at the municipal level and use of mortality data would make little difference than using morbidity data because of the low 5-year survival rate of lung cancer.

In several studies, the population attributable risk percent of the total number of radon-induced lung cancer deaths was given and indicated higher percentages among never-smokers (Chen et al., 2012; Grundy et al., 2017; Menzler et al., 2008; Peterson et al., 2013; Veloso et al., 2012). This finding indicates that while lung cancer among never-smokers constitutes a small percentage of the total number of lung cancer deaths, exposure to radon is the major contributor to the development of lung cancer among non-smokers. However, due to the absolute risk of lung cancer found when combining exposure to smoking and radon, a greater number of radon-induced lung cancer deaths occurred among those with a history of smoking. Additionally, results indicated a stronger synergistic effect among males, likely due to different smoking patterns and differing relative risk of lung cancer due to smoking between sexes. For example, in Alberta Canada, Grundy et al. (2017) estimated an overall population attributable risk from radon exposure of 16.6%. When smoking and sex was accounted for, the estimated population attributable risk percent was 26.2% among male never-smokers, 17% among males exposed to smoking and radon, and 16% among male ever-smokers, resulting in 95, 953, and 856 observed lung cancer deaths, respectively. In comparison, estimated

population attributable risk percent was 24.6% among female never-smokers, 15.8 % among females exposed to smoking and radon, and 15.3% among female ever-smokers, resulting in 100, 999, and 900 observed lung cancer deaths, respectively.

2.3.7 Effects of Radon Mitigation

In addition to determining the percentage of lung cancers attributable to radon exposure, Chen et al. (2012), Menzler et al. (2008), and Peterson et al. (2013) set out to describe the proportional reduction in population mortality that would occur if residential radon concentrations were reduced across the population. In Ontario, Canada, calculations were repeated after making all homes at or above 50, 100, 150 or 200 Bq/m^3 to background levels and found 389, 233, 149, and 91 radon attributable lung cancer deaths, respectively, could be prevented annually (Peterson et al., 2013). The varying proportion of lives saved was related to the proportion of homes found within each concentration interval; more homes were found to have radon concentrations at or above 100 Bq/m^3 than 150 Bq/m^3 and 200 Bq/m^3. The theoretical reduction in radon exposure was similar to findings by Chen et al. (2012) and Menzler et al. (2008). In Ontario, Chen et al. (2012) estimated 927 radon-induced lung cancer deaths could be prevented if all homes above the Canadian action level of 200 Bq/m^3 were mitigated to levels below the action level. In comparison, if all homes above 800 Bq/m^3 were mitigated to outdoor concentrations, 90 lives would be saved annually. The difference in lives saved was because the majority of the population is exposed to low concentrations of radon in their homes. Menzler et al. (2014) reported that reducing all homes with concentrations higher than 100 Bq/m^3 (2.7 pCi/L) to 100 Bq/m3, would save 302 lives annually (Menzler et al., 2014). To demonstrate a greater effect of mitigation, if homes in Germany were cut to the

same concentration as outdoor air, 1,896 lung cancer deaths could be prevented annually (Menzler et al., 2014).

2.4. Discussion

This systematic literature review summarized nine descriptive epidemiologic studies which sought to estimate the proportion of lung cancer that could be attributed to residential radon exposure in Europe, Korea, and Canada. The population attributable risk percent from radon exposure ranged from 5-28%. The variation in estimated attributable risk among the nine studies was related to the varying lung cancer mortality rate and population within the study area, the population-weighted mean radon concentration of the study area, variation in smoking prevalence in the population, and which risk model was utilized to calculate excess relative risk.

All studies reviewed utilized lung cancer mortality as opposed to lung cancer incidence when calculating attributable risk. This may be due to the lack of available incidence data in some countries, as was the case in France (Ajrouche et al., 2018). However, it is possible that the use of mortality data could underestimate attributable risk as those who survive a diagnosis of lung cancer would not have been included in the calculation. The use of lung cancer incidence data, over mortality data, would include all cases of lung cancer and yield a more accurate estimate of attributable risk of radon-induced lung cancer. However, the American Cancer Society estimates only 16% of lung cancers in the United States are expected to be diagnosed at a localized stage and the 5-year relative survival rate for lung cancer is 19% (ACS, 2020). Therefore, the use of lung cancer mortality data is likely to yield an estimate of attributable risk similar to that which would be found using incidence data due to the low survival rate associated with

lung cancer. As lung cancer screening utilization and treatments for lung cancer improve over time, 5-year relative survival rates may increase. Therefore, investigators should consider the use of lung cancer incidence data in the future.

A concern inherent in risk estimation related to radon exposure is that it is largely dependent upon the accuracy of the radon measurement. The concentration of radon in the air can be measured using short-term, long-term, continuous, and grab sample devices (WHO, 2009). While short-term measurement and grab sample devices provide an initial indication of the mean long-term radon concentration in a home, the short period of measurement does not account for daily and seasonal variation in air radon concentration. Therefore, long-term measurement of radon concentration is the preferred method for estimating long-term radon exposure and making decisions about mitigation (WHO, 2009). The use of radon concentrations gathered from the use of long-term alpha-track radon measurement devices by Chen et al. (2012), Grundy et al. (2017), Peterson et al. (2013), Truta-Popa et al. (2010), and Veloso et al. (2012) over the period of 1-3 months was seen as a strength in those studies. The remaining four studies did not provide details on how radon was measured which is a limitation.

Additionally, studies conducted in Canada (Chen et al., 2012; Grundy et al., 2017; Peterson et al., 2013) and Portugal (Veloso et al., 2012) failed to correct radon measurements for seasonality. Radon exposure data utilized in the Canadian studies were obtained from the Health Canada's Cross-Canada Survey of Radon Concentrations in Homes. These measurements were collected in the fall and winter seasons of 2009/2010 and 2010/2011. As radon concentrations in homes tend to be highest in the colder months (i.e., windows and doors are not open to fresh air), the lack of correction for seasonal

variation likely led to an overestimation of mean radon concentration in the population. In Portugal, measurements were taken over 1-3 months and measured twice in each house when possible, however seasonality was not addressed (Veloso et al., 2012). The radon data which likely demonstrated the greatest accuracy were gathered in Switzerland. Measurements were collected from occupied rooms of 45,361 homes and corrected for seasonality, adjusting for which floor of the home the radon measurement was obtained, and then averaged the values by the number of homes within the community and weighted by population size (Menzler et al., 2008). The additional adjustment by floor level is seen as a strength as mean first- and second-floor radon concentrations are half that of the concentrations detected in the basements of homes (Field et al., 2000).

As smoking is the leading cause of lung cancer, use of smoking prevalence data specific to the area under study is seen as a strength in many of the studies included in this review. Making assumptions about a smoking population which may not be a true representation of the population under study, as was done by Truta-Popa et al. (2010) and Veloso et al. (2012), may produce inaccurate population attributable risk percentages.

The models used to estimate excess relative risk for a lifetime of exposure to radon varied, with the majority of studies (Ajrouche et al., 2018; Bochicchio et al., 2012; Lee et al., 2015; Menzler et al., 2008; Truta-Popa et al., 2010) utilizing the European Pooling Model (Darby et al., 2005). The European Pooling Model was derived from the analysis of 13 case-control residential radon exposure studies. The analysis resulted in the largest set of residential radon exposure data to-date from which investigators used to assess attributable risk of radon-induced lung cancer. Prior to the European Pooling study, relative risk was largely determined by utilizing the Exposure-Age-Concentration

(EAC) and Exposure-Age-Duration (EAD) models proposed in the BEIR-VI report (NRC, 1999). The risk estimates gathered using EAC and EAD models are often scrutinized because of the uncertainties associated with residential radon exposure risk estimates being extrapolated from miners to the public. Uncertainties stem from the differences in radon concentrations found in mines and homes, sex, age, smoking history, respirations and ventilation and varying vital statistics data over time (NRC, 1999). In general, miners are exposed to high levels of radon and other air pollutants that would normally not be found in a residence. Furthermore, the miner samples were largely composed of adult males and there is concern as to whether or not the model is applicable to women and children. The BEIR-VI committee addressed these concerns and could not identify evidence demonstrating differing susceptibility to lung carcinogens by sex and they extended the model to women. In addition, there was no clear reason to not extend the model to children (NRC, 1999).

With the exception of Menzler et al. (2008), each study utilized a theoretical radon concentration of 0 Bq/m^3 as the reference level to calculate excess relative risk for unexposed populations, indicating a completely radon free environment for the unexposed. Menzler et al. (2008) calculated excess relative risk of the unexposed utilizing a baseline concentration of radon equal to concentrations that would naturally be found outdoors in the respective countries. In doing so, the calculations were seen as a more accurate representation of radon exposure in the 'unexposed' as zero exposure to radon is unlikely. As radon is naturally occurring and ubiquitous, a concentration of 0 Bq/m^3 is not realistic and is seen as a limitation to many of the studies. The use of 0 Bq/m^3 to describe the unexposed population, may also lead to an overestimation of the

excess relative risk. Rockhill et al. (1998) suggests that when modifiable risk factors are explored in order to prioritize public health interventions, the exposure cut point chosen to describe the 'unexposed' needs to be realistically attainable. Furthermore, each study calculated the excess relative risk with the assumption that the population was exposed to the same radon concentration level throughout their lifetime. This assumption does not reflect reality as radon concentrations fluctuate by season, and room to room, and does not account for people moving to different homes, all contributing to varying exposure levels over the course of a lifetime.

The population attributable risk percentages ranged from 5% in counties of Transylvania, Romania and Germany (Truta-Popa et al., 2010; Menzler et al., 2008) to 28% in Korea and Portugal (Lee et al., 2015; Veloso et al., 2012). Variability is likely due to the varying radon risk potential and population size, however, it is suggested by Menzler et al. (2008) that discrepancies found between population attributable percentages may also be due to the lack of correction for uncertainties in radon distribution, use of an unachievable no-exposure threshold of background radon concentration of 0 Bq/m^3 when calculating the excess relative risk, and different assumptions regarding the relevant time of exposure and the overestimation of the relevant exposure by the BEIR-VI models, especially in older age groups. In each study which used both the European Pooling Model and the BEIR-VI models, estimates of population attributable risk were higher utilizing the BEIR-VI models. An advantage to the use of the European Pooling Model is that it was derived from analysis of residential radon data and not subject to the uncertainties associated with extrapolation of results from miners to the general public as with the BEIR-VI EAC and EAD models.

Findings from several of the studies which compared the population attributable risk percent of radon-induced lung cancer deaths across smoking categories indicate that exposure to radon is a leading cause of lung cancer deaths among never-smokers (Chen, 2012; Grundy et al., 2017; Menzler et al., 2008; Peterson et al., 2013; Veloso et al., 2012). However, due to the higher absolute risk of lung cancer from the combined effects of smoking and radon, ever-smokers most often incurred a greater number of deaths due to residential radon exposure than never-smokers. This was also true in the studies reported in the BEIR-VI report (NRC, 1999). Additionally, a stronger synergistic effect was seen among males and was likely due to higher prevalence of smoking among males than females. Despite variations in population attributable risk percentages, studies demonstrated that exposure to residential radon is a cause for the development of lung cancer, particularly among smokers. One limitation noted in all studies was the lack of consideration given to the combination of secondhand smoke exposure and radon in the home. Secondhand smoke exposure has long been recognized as a major cause of lung cancer (US Department of Health and Human Services, 2014) and evidence suggests that among never-smokers, exposure to residential radon may be more harmful for those also exposed to secondhand smoke (Lagarde et al., 2001).

The studies which hypothetically reduced population exposure to residential radon through radon mitigation demonstrated a potential reduction in lung cancer mortality. The greatest reduction was seen when all homes were mitigated to that of outdoor levels. In the three studies, when homes above the World Health Organizations action level of 100 Bq/m^3 were reduced to that of outdoor air, 1704 (Chen et al., 2012); 1896 (Menzler et al., 2008); and 233 (Peterson et al., 2013) deaths could have been

prevented annually. Additionally, the majority of radon-induced lung cancer occurred among those exposed to low concentrations in their homes. So, while exposure to a radon concentration of 800 Bq/m^3 over a lifetime is a greater risk for lung cancer compared to exposure to 100 Bq/m^3 over a lifetime, more radon-induced lung cancers occurred among those living in lower concentrations due to the greater number of people living with lower radon concentrations. These findings highlight the importance of risk messaging which emphasizes that there is no safe level of radon exposure and the establishment of accessible and affordable radon mitigation programs.

2.4.1 Future Implications

Descriptive epidemiologic methods utilize exposure data at the population level rather than the individual level (Paddle & Harrington, 2000). Limitations are inherent in the use of such data, and the use of data from representative samples are ideal. In future studies which aim to determine population attributable risk of radon-induced lung cancer, collecting residential radon concentrations at the finest geographical level from representative samples of the population under study, and correcting for uncertainties in the measured radon concentrations are critically important. In addition, smoking prevalence data specific to the population are needed in order to calculate the best estimates. As many individuals are exposed to secondhand smoke in homes, worksites, and public places, future studies should consider the contribution secondhand smoke has in the development of radon-induced lung cancer. Additionally, with improvements in early detection and treatment of lung cancer, consideration needs to be given to the use of lung cancer incidence data as opposed to mortality data when calculating population attributable risk in order to capture the true total number of lung cancer cases. Finally, given the uncertainties associated with extrapolation of results from miners to the general

public, as per the BEIR-VI EAC and EAD models, additional well designed case-control studies using residential radon measurements would add to the science and provide further evidence for the use of a residential radon model (e.g., European Pooling Model) over models developed from studies of miners.

In conclusion, exposure to residential radon is a public health concern that demonstrates an increased risk for lung cancer, particularly among ever-smokers. Given the disparities in smoking prevalence and lack of home radon testing in the U.S., quantification of the proportion of lung cancer cases associated with residential radon exposure in each state may be useful to public health officials and state radon programs. Such information could be used to guide public policies aimed at reducing radon concentrations in homes, schools, and other public places. As more radon-induced lung cancer occurs among smokers, particular attention is needed to create smoke- and radon-free homes and other indoor spaces. The additional quantification of the number of lives saved through radon mitigation could provide further evidence for the development of public policies and accessible, affordable programs aimed at reducing smoking and radon concentrations in homes.

Table 2.1

Summary of Retained Articles for Systematic Review

Author, Year	**Country**	**Purpose**	**Model used for ERR calculation**	**Variables/Measurement**	**Findings**
Ajrouche, 2018	France	Estimate the lung cancer mortality risk in France attributable to indoor radon exposure	European Pooling Study	- 2012 population census - Lung cancer deaths 2008-2012 - 1982-2003 National survey of radon concentrations (10,843 homes) - 2010 smoking prevalence - PAF - Total # of lung cancer deaths attributable to radon exposure - Lung cancer deaths attributable to radon calculated separately by smoking status	- 70 Bq/m^3 national population-weighted average indoor radon concentration - Estimated number of lung cancer deaths per year attributable to indoor radon exposure is 2199 (95% CI 757; 3811) in men and 725 (95% CI 249; 1257) in women - 9.6% of lung cancers attributable to radon - 66% of deaths attributed to radon occur in exposure less than 100 Bq/m^3 - 75% of lung cancer deaths attributable to indoor radon exposure occur among current smokers; 20% ex-smokers; 5% never-

Table 2.1 (continued)

Author, Year	Country	Purpose	Model used for ERR calculation	Variables/Measurement	Findings
					smokers
Bochicchio 2013	Italy	Evaluate the total number of LC attributable to radon exposure in dwellings, and separately by smoking status	European Pooling Study	- Lung cancer death (2003-2008 mean) - Smoking prevalence 2005 - National Survey of radon measurements: 1990s - Census data 2001 for total population - PAR	- Mean 71 Bq/m^3 - Av. annual lung cancer deaths 32,642 - 10% of lung cancer in Italy are attributable to radon; percentage varies 4-16% depending upon region and is proportional to the average radon concentration in the region - 3366 lung cancer deaths can be attributed to radon in Italy (2604 males; 762 females). - Among females, 6.3% of all lung cancers among current smokers are attributable to radon; 1.3% among former smokers; 2.9% among never smokers.

Table 2.1 (continued)

Author, Year	Country	Purpose	Model used for ERR calculation	Variables/Measurement	Findings
					- Among males, 7.3% of all lung cancers among current smokers are attributable to radon; 2.4% among former smokers; 0.5% among never smokers. - 72% lung cancer attributed to radon among males occurs in current smokers; 60% among female current smokers - 24% of lung cancer attributed to radon in males is among ex-smokers and 5% among never smokers - 13% of lung cancer attributed to radon in females is among ex-smokers and 28% among never smokers.
Chen, 2012	Canada	Re-assessment of the Canadian	EPA	- National Survey Radon - Age specific mortality	- Log-normal distribution of radon

Table 2.1 (continued)

Author, Year	Country	Purpose	Model used for ERR calculation	Variables/Measurement	Findings
		population risk for radon induced lung cancer		averaged from 1996-2000 - Smoking prevalence 2002 - Lung cancer mortality 2011 - AR	measurements - Geometric mean radon 41.9 Bq/m^3 - 15.3% of lung cancer deaths attributable to radon in men occur in ever smokers; 29.5% in never-smoker. - 14.3% of lung cancer deaths attributable to radon in females occur in ever-smoker; 27.8% in never-smoker. - In 2011, 1805 lung cancers in men were attributable to radon exposure (1639 in ever-smoker; 166 in never smoker). - In 2011, 1456 lung cancers in women were attributable to radon exposure (1198 in ever-smoker; 258 in never smoker)
Grundy	Canada	Estimate the	BEIR VI	- 2011 Census data	- Geometric mean of

Table 2.1 (continued)

Author, Year	Country	Purpose	Model used for ERR calculation	Variables/Measurement	Findings
2017		population attributable risk of lung cancer due to residential radon exposure in Alberta and to estimate the number of cases of lung cancer that could be attributed to this exposure in 2012.	EAC	- National Radon Survey 2009-2011 (1076 in Alberta) - Prevalence from national survey 2000-2001, 2003, 2005 and 2007-2008 - All-cause mortality for 2008-2012 - Lung cancer mortality - life-table methods used to estimate lifetime risk of lung cancer mortality among radon-exposed and unexposed	71.0 Bq/m^3 - Mean PAR of 16.6% when not accounting for smoking status, accounting for 324 excess cases of lung cancer attributable to radon in 2012 - Mean PAR was higher among never smokers than ever smokers in the total population as well as when separated by gender, 24.8% among never smokers; 15.6% among ever smokers.
Lee 2015	Korea	estimate the population attributable fraction of radon-induced lung cancer deaths by gender across Korean administrative districts	BEIR-VI European Pooling Study	- National radon survey, 1989, 2000, 2002-2005, 2008-2009; - lung cancer mortality 2000-2012, Korea National Statistical Office - proportion of lung cancer attributable to smoking obtained from a large Korean cohort study (2004)	- average 62.1 Bq/m^3 - 13.5%-19.5% and 20.4%-28.2% of lung cancer deaths in males and females respectively attributable to radon (EAD and EAC models) - PAF 8.3% (European

Table 2.1 (continued)

Author, Year	Country	Purpose	Model used for ERR calculation	Variables/Measurement	Findings
				- PAF	Pooling) - smoking alone caused most deaths in males (76.5-81.9%), radon alone the fewest (1.5-2%); Females, issues other than smoking and radon produced the most attributable deaths (45.7-51.7%); joint effects of radon and smoking the fewest (4.1-5.9%)
Menzler 2008	Switzerland and Germany	Present PAF calculations for Switzerland and Germany based on the most recent available estimates of the distribution of radon concentrations in homes and on the risk model derived from the collaborative	European Pooling Study	- National radon data from 45,361 homes Switzerland - National radon data from 32,336 homes in Germany - Lung cancer mortality 2001 Switzerland; 1996-2000 annual average Germany - Smoking national data from Swiss Federal Office for Statistics 2002-2003; National survey 1991-1992	- geometric mean 55 Bq/m^3 in Switzerland - geometric mean 49 Bq/m^3 - Total PAF Switzerland 8.3%; Germany 5.0%. - Higher PAF in nonsmokers. - 231 deaths in

Table 2.1 (continued)

Author, Year	Country	Purpose	Model used for ERR calculation	Variables/Measurement	Findings
		European analysis		West Germany, 1991-1992 East Germany	Switzerland attributable to radon; 1896 in Germany - 218 of the deaths attributable to radon in Switzerland occurred in smokers - 1737 of the deaths attributable to radon in Germany occurred in smokers
Peterson 2013	Canada	Calculate the burden of lung cancer illness due to radon for all thirty-six health units in Ontario and determine the number of radon-attributable lung cancer deaths that could be prevented	BEIR-VI EAC	- Health Canada's Cross-Canada Survey of Radon Concentrations in Homes 2009-2011(n=3891) - all-cause mortality by health unit, Intelli-HEALTH Ontario - RR of all-cause mortality from smoking from American Cancer Society - RR of lung cancer mortality from smoking (ACS) - Lung cancer mortality by health unit, Intelli-HEALTH	- lognormal distribution of radon measurements - geometric mean 43 Bq/m^3 - 13.6% of lung cancer deaths in Ontario are attributable to radon. - ~84% of the deaths attributable to radon occurred in ever-smokers - PAR % were higher in never-smokers,

Table 2.1 (continued)

Author, Year	Country	Purpose	Model used for ERR calculation	Variables/Measurement	Findings
				Ontario - Prevalence of ever-smokers by health unit, Canadian Community Health Survey - PAR%	mean of 21.95% - PAR % lower in ever-smokers, mean of 12.3% - In 2007 ~840 lung cancer deaths in Ontario were attributable to radon - In 2007, ~700 of the lung cancer deaths attributable to radon were in ever-smokers - if all homes ≥ 200 Bq/m^3 were remediated to background, 91 radon-related lung cancer deaths would be prevented; ≥ 150 Bq/m^3 were remediated to background, 58 deaths prevented; ≥ 100 Bq/m^3 were remediated to

Table 2.1 (continued)

Author, Year	Country	Purpose	Model used for ERR calculation	Variables/Measurement	Findings
					background, 84 deaths prevented; ≥ 50 Bq/m^3 were remediated to background, 389 deaths could be prevented.
Truta-Popa 2010	Romania	Assess lung cancer risk due to radon exposure for populations living in selected regions of Transylvania, Romania. Estimate the fraction of lung cancer cases attributable to radon in each region	European Pooling Study	- smoking rates from one region (Stei) used to estimate for all regions - Indoor radon measurements from a representative sample of 667 dwellings; Alpha track detectors 3 months, during summer and winter and corrected for seasonal variation. - lung cancer mortality rates from 2006-2008 from the Institutul National de Statistica - Population data from the Institutul National de Statistica - Relative Risk of lung cancer	- mean, weighted annual radon concentrations ranged from 62-232 Bq/m^3 - Fraction of lung cancer attributable to radon among non-smokers ranged from 4.76%-16.67% - 64%-69% of male lung cancer deaths attributable to radon occurred in smokers - 35-44% of female lung cancer deaths attributable to radon occurred in smokers

Table 2.1 (continued)

Author, Year	Country	Purpose	Model used for ERR calculation	Variables/Measurement	Findings
				using European Pooling Study - number of total lung cancer deaths due to indoor radon - attributable fraction	- total annual lung cancer mortality attributable to radon was estimated at 806 with approximately 472 occurring in male smokers and 275 occurring in female smokers.
Veloso 2012	Portugal	Assess the risk of lung cancer and estimate, for the northern region of Portugal, the number of lung cancer deaths, between 1995-2004, attributable to indoor radon exposure	BEIR VI EAD EAC	- 2001 census population data - lung cancer mortality 1995-2004 from the North Regional Health Administration Radon survey 1987-1995; weighted district average used to obtain radon exposition level for each district - Smoking data from prior study 1995-2000; used 2 methods to calculate smoking; the data from study and the assumption that 95% and 90% of all lung cancer deaths are from smokers.	- lognormal distribution of radon concentrations - geometric mean 66.77 Bq/m^3 - 18-28% of lung cancer deaths could be attributed to indoor radon exposure - proportion of lung cancer deaths associated with radon was higher among non-smokers than smokers

Table 2.1 (continued)

Author, Year	Country	Purpose	Model used for ERR calculation	Variables/Measurement	Findings
				- *N* calculation	- approximately 10x more deaths occurred among smokers than non-smokers - EAC produced higher values than EAD, although close - 20-27% of lung cancer deaths in males attributable to radon; of those, 90% occurred in smokers - 27-34% of lung cancer deaths in females attributable to radon; of those, 80% occurred in smokers. - AF higher in non-smokers than smokers

Notes. ERR = excess relative risk. RR = relative risk. AF = attributable fraction. PAF = population attributable fraction. PAR = population attributable risk.

Table 2.2

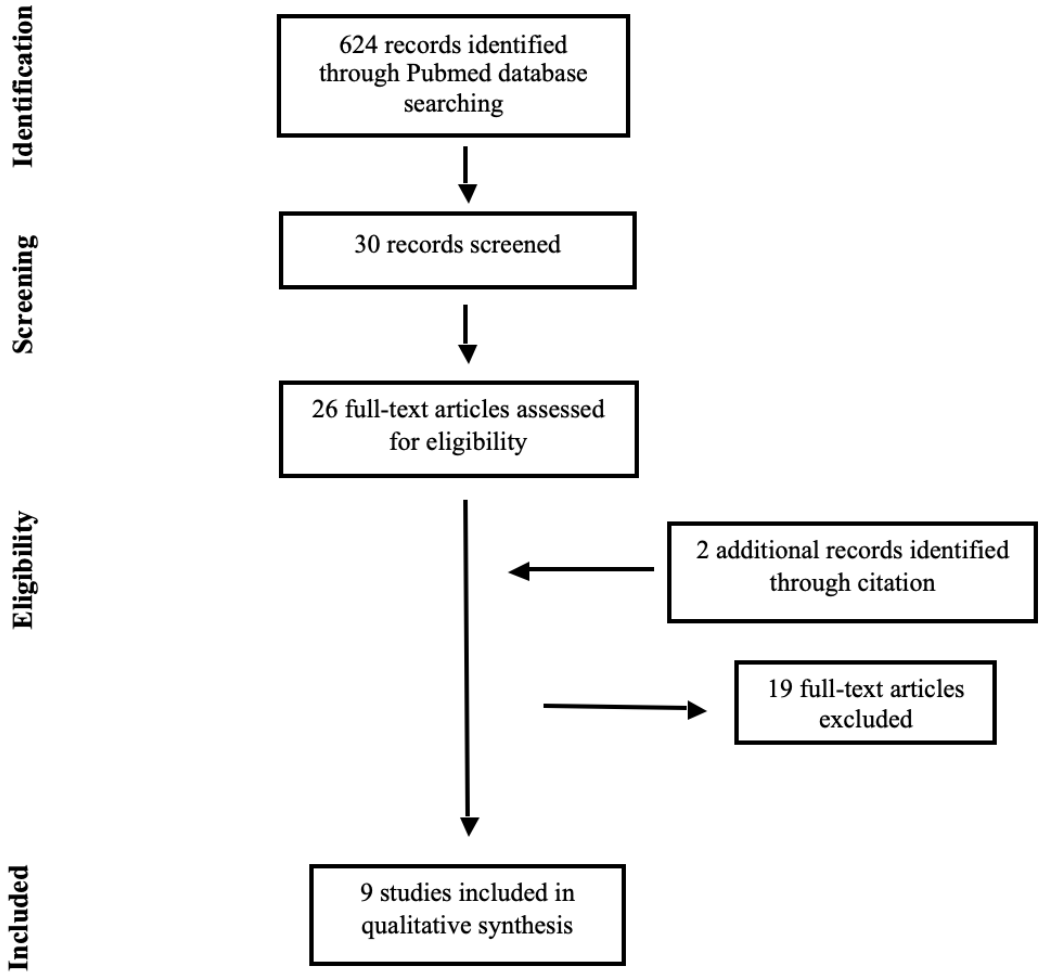
Estimates of the Population Attributable Risk Percent of Radon-induced Lung Cancer in Selected Studies

Country	**Mean indoor radon Bq/m^3 *(pCi/L)**	**Risk estimate used in calculation**	**PAR %**	**Lung cancer mortality attributable to radon**		
				Male	Female	Total
France	70 (1.89)	European Pooling	9.62	2199	725	2924
Italy	71 (1.91)	European Pooling	10	2604	762	3366
Canada	42 (1.14)	EPA	16	1805	1456	3261
Canada	71 (1.91)	BEIR VI	16.6	162^	158^	324^
Korea	62 (1.68)	European, BEIR VI	8-28	11,906-26,782*	4,271-13,695**	16,177-40,477**
Switzerland	78 (2.11)	European Pooling	8.3	169	62	231
Germany	49 (1.32)	European, BEIR VI	5.0-12	1422^^	474^^	1896^^
Canada	43 (1.16)	BEIR VI	13.6	-	-	847
Portugal	81 (2.19)	BEIR VI	18-28	1294-1880	271-526	1565-2406
Romania	62-232 (1.68-6.27)	European Pooling	5-17	-	-	806

Notes. *Equivalent concentration in pCi/L. **Deaths over a 20-year period from 1989-2009. ^ refers to estimated lung cancer cases. ^^ refers to estimates derived using the European Pooling Model only. PAR = population attributable risk.

Figure 2.1

Flow Diagram of Systematic Literature Search



CHAPTER 3:

PREDICTORS OF HOME RADON TESTING IN RURAL APPALACHIAN KENTUCKY

3.1. Background

Lung cancer, a highly preventable form of cancer, is the second most commonly diagnosed cancer, and the leading cause of cancer mortality in the United States (American Cancer Society [ACS], 2020). In 2020, the American Cancer Society estimates 228,820 new cases of lung cancer and approximately 135,720 deaths from the disease in the U.S. (ACS, 2020). Cigarette smoking is the leading cause of lung cancer, followed by radon gas exposure and exposure to secondhand smoke (SHS) (ACS, 2020). In the U.S., radon exposure is associated with approximately 21,000 new cases of lung cancer each year and of those, approximately 2,900 occur in individuals who have never smoked tobacco (Environmental Protection Agency [EPA], 2019). While radon exposure is a cause of lung cancer among smokers and non-smokers, a synergistic effect exists between tobacco smoke and radon exposure in the development of lung cancer. Those who are exposed to tobacco smoke and are exposed to radon have a 10-fold greater risk of developing lung cancer than non-smokers and those not exposed to tobacco smoke (EPA, 2019).

Human exposure to radon occurs largely in the home and the EPA estimates that one in every 15 homes in the United States has a high radon level (EPA, 2016a). While there is no safe level of radon exposure, the EPA and the U.S. Surgeon General advise all Americans to test for radon in their home and take action to reduce indoor radon concentration when the radon level is $\geq$ 4.0 picocuries per liter of air (pCi/L) (EPA, 2016b; United States Department of Health and Human Services, 2005). Various radon

reduction methods exist, however the primary method is through the installment of a mitigation system (EPA, 2016b).

Testing one's home for radon is necessary to determine exposure risk. Despite public awareness of radon, the proportion of people who have completed home radon testing remains low, ranging from 3-15% of those surveyed (Eheman et al., 1996: Wang et al., 2000). Factors that contribute to home radon testing are: higher income (Halpern & Warner, 1994; Hill et al., 2006; Nissen et al., 2012; Zahnd et al., 2017); higher education (Butler et al., 2018; Halpern & Warner, 1994; Nissen et al., 2012; Zahnd et al., 2017); urbanicity (Zahnd et al., 2017); younger age (Halpern & Warner, 1994; Wang et al., 2000); female sex (Halpern & Warner, 1994); home ownership (Hill et al., 2006; Wang et al., 2000); presence of children in the home (DiPofi et al., 2001); health concerns (Nissen et al., 2012; Rinker et al., 2014); knowledge of radon (Duckworth et al., 2002; Wang et al., 2000); perceived community radon risk (Weinstein et al., 1991); living in a high-risk radon zone (Wang et al., 2000; Zahnd et al., 2017); perceived severity (Duckworth et al., 2002; Weinstein et al., 1991); perceived susceptibility and social influence (Rinker et al., 2014; Weinstein et al., 1991); availability of free or discounted testing kits (Nissen et al., 2012; Butler et al., 2018); discussion with a real estate agent (Neri et al., 2018); and physician recommendation (Nissen et al., 2012).

Kentucky leads the nation in incidence and mortality from lung cancer in both men and women (ACS, 2020). The Central Appalachian region of the state contributes to the vast majority of the lung cancer incidence and mortality with average age-adjusted lung cancer incidence and mortality rates higher than in the non-Appalachian region (Kentucky Cancer Registry [KCR], 2019a; KCR 2019b). The Kentucky Behavioral Risk

Factor Survey 2018 Annual report indicates 24.5 % of adults in Kentucky are current smokers (compared to 17.1 % of the nation) and adult smoking rates in each of the five Appalachian Area Development Districts exceed that of the state (range 24.8%- 32.2%; Department for Public Health, Cabinet for Health and Family Services, 2018). Additionally, many Kentuckians are exposed to SHS in their home or workplace. The National Adult Tobacco Survey, 2009-2010, found that approximately one-third of Kentucky homes lack rules which prohibit smoking indoors (King et al., 2013) and only approximately 36% of Kentuckians are currently protected by smoke-free laws covering all indoor workplaces and public places (Kentucky Center for Smoke Free Policy, 2019). In addition, the EPA (1993) has labeled all counties in the Appalachian region of Kentucky as having moderate potential for elevated indoor radon concentrations, raising concern for the synergistic effect of tobacco and radon on the development of lung cancer among residents of Appalachia Kentucky. Despite the alarming lung cancer rates, there is little evidence of radon testing in the region and mitigation rates are unknown.

In a database of over 60,000 observed radon values in Kentucky from 1986-2014, a total of 10,245 radon values were recorded in Appalachia Kentucky (total housing units, 539,633; 2% testing rate over 28 years) (Pollard & Jacobsen, 2016; Radon Policy Division, unpubl. Data). The relatively unknown radon levels and mitigation rates in the region, coupled with the potential for synergistic risk are an environmental health concern. To complicate this public health concern, Appalachian Kentuckians are disproportionately challenged by high levels of poverty, and low levels of income and postsecondary education (Pollard & Jacobson, 2016).

To date, two investigators have examined radon risk perception and testing in a rural population (Duckworth et al., 2002; Hill et al., 2006). In a sample of 31 residents of rural Montana, Hill et al. (2006) found that residents had basic knowledge of radon by indicating they could not taste, smell or see radon. However, over one-third of participants disagreed with the statement, "health effects due to radon are likely to be serious." Hill et al. (2006) reported significant positive associations between home ownership, income and radon testing among rural Montana residents. In another study of rural residents of DeKalb County, Illinois ($N = 473$), Duckworth et al. (2002) found that females and younger participants were significantly more likely to perceive radon as a health hazard, and perceiving radon as a serious health hazard was significantly associated with planning to test for radon.

Eliminating exposure to tobacco smoke and reducing exposure to radon are important primary prevention strategies to reduce the incidence and mortality from lung cancer. Given the Appalachian region's high lung cancer rates and widespread tobacco use, the relative lack of radon testing in the region is a public health concern that necessitates further exploration. Exploring factors associated with home radon testing among rural Appalachia Kentucky residents is needed to assist public health workers in their efforts to engage residents in taking action to reduce elevated indoor radon levels. Primary care practitioners in the region are in the unique position to influence radon testing by creating teachable moments during medical visits. Health events, such as doctor visits, are thought to be prime opportunities for teachable moments as they often raise an individual's motivation for behavior change (McBride et al., 2003).

Knowing that not everyone who experiences a health event makes behavioral changes, McBride et al. (2003) developed the Teachable Moment Model (TMM) to guide research on individual health behavior change (Figure 3.1). The TMM suggests that individuals are more likely to take action when they experience a health event that causes them to reflect upon their beliefs and knowledge about their own health, increases their perception of personal risk, and creates a strong affective or emotional response (McBride et al., 2003). In addition, this subjective assessment of health events may be influenced by an individual's sociodemographic characteristics (McBride et al., 2003). As such, we used the TMM to guide this research. As more radon-induced lung cancers occur in those with a history of tobacco smoke exposure, an additional construct, perceived synergistic risk, was added in order to better understand its contribution to taking action to reduce residential radon in rural Appalachia.

The primary aims of this exploratory, prospective study were to: 1) compare differences in sociodemographic characteristics, personal risk perception, emotional response as measured by lung cancer worry, and synergistic risk perception differences among rural Appalachia residents who completed home radon testing with those who did not, after receiving a free long-term test kit at a rural primary care clinic; and 2) examine the association between the Teachable Moment Model constructs of personal risk perception, emotional response, and synergistic risk perception and home radon testing in a small sample of rural Appalachian residents. It was hypothesized that participants with higher perceived personal lung cancer risk, greater lung cancer worry scores, and higher synergistic risk perception would be more likely to test their home for radon after receiving a free radon test kit at their primary care office compared to those with lower

perceived personal lung cancer risk, less lung cancer worry, and lower synergistic risk perception.

3.2. Methods

3.2.1 Design and Sample

This was an exploratory, prospective, non-experimental study. Quantitative methods were used to analyze findings from a self-report survey and environmental exposure assessment. A convenience sample of 58 adult participants was recruited from two rural primary care clinics located in Appalachian Kentucky. Both primary care clinics are affiliated with a regional medical center located in Central Appalachian Kentucky. Healthy males and females aged 18-90 years and of all racial/ethnic groups who were able to speak and read English were invited to participate, regardless of whether or not they owned their home. Prior to recruitment, two investigators conducted a lunch-and-learn session with clinic staff to review study procedures and provide information on radon risks, testing, and mitigation.

All patients with clinic appointments were approached by the clinic receptionist at check-in to determine potential interest in the research study. If the patient expressed interest, the clinic receptionist provided a brief confidential paper-and-pencil survey to complete on-site with a cover memo explaining the study and a free radon test kit. The University of Kentucky Institutional Review Board granted a waiver of documentation of informed consent due to the logistics of conducting research in a busy clinic waiting room. Enrollment began in August 2015, and participants were asked to deploy the radon test kit no later than mid-September 2015. Participants received reminder phone calls to deploy their test kit one week after enrollment, and again 90-days after enrollment to

remind participants to return their test kit using the postage-paid envelope. Of the 58 test kits distributed, 28 participants (48%) deployed and returned the test kits for analysis. The study was approved by the University of Kentucky Medical institutional review board.

3.2.2 Measures

3.2.2.1 Sociodemographic/Personal Characteristics

Sociodemographic and personal characteristics including age (in years), length of time at current residence (in years), sex, education, marital status, race/ethnicity, employment, household income, home ownership, presence of children in the home, presence of SHS in the home, and personal smoking status were obtained via self-report survey. Participants were asked to identify sex as male, female, or transgender. Education was assessed by asking participants to indicate the highest grade or year of school completed: a) never attended school/only kindergarten, b) grades 1-8 (elementary), c) grades 9-11 (some high school), d) grade 12 (high school graduate), e) GED (General Equivalency Diploma), f) 1-3 years of college (some college or technical school), g) 4 years of college or more (college graduate), or h) postgraduate education. Due to too few responses in some categories, responses were recoded to “less than HS”, “high school graduate/GED”, or “greater than high school.” To assess marital status, participants were asked if they were: a) married, living with spouse, b) married not living with spouse, c) divorced, d) widowed, e) separated, f) never been married, or g) unmarried couple living together. Those who responded “married, living with spouse” and “married, not living with spouse” were coded as “yes”, all others were coded as “no.” Race was assessed by asking “Which of the following best describes your race?” a) American Indian/Alaskan Native, b) Asian, c) Native Hawaiian or Other Pacific Islander, d) Black or African

American, e) White, f) More than one Race. Participants chose between a) Hispanic or Latino or b) Not Hispanic or Latino to indicate their ethnicity. Due to few participants identifying in minority racial and ethnic categories, we combined variables and categorized as "White/non-Hispanic" and "Other". Participants were asked to indicate current employment status including a) employed for wages, b) self-employed, c) out of work for less than one year, d) out of work for more than one year, e) homemaker, f) volunteer, g) student, h) retired, i) disabled/unable to work. Responses were then dichotomized into "employed/retired" for all those who indicated "employed for wages", "self-employed" and "retired" and "unemployed/disabled" for all others. Annual household income was measured using the following categories: a) less than $15,000, b) $15,000-$29,999, c) $30,000-$44,999, d) $45,000-$59,999, e) $60,000-$74,999, f) $75,000-$89,999, g) $90,000- $104,999, h) $105,000- $119,999, and i) $120,000 or more. Due to too few responses in some categories, responses were dichotomized into "less than $30,000" and "greater than or equal to $30,000". This cut point value was chosen as nearly half of respondents reported income less than $30,000. Home ownership was identified by asking participants to choose whether they owned or rented their home. Presence of children in the home was assessed by asking how many people under the age of 18 live in their current residence. Those who indicated "0" were coded as "no", those who indicated any value greater than or equal to 1 were coded as "yes".

3.2.2.2 Tobacco Smoke Exposure

Presence of SHS in the home was assessed by asking, "What is the likelihood of there being secondhand smoke in the place where you live?" (4-point Likert scale ranging from (1) very unlikely" to (4) "very likely"). Those who responded "very unlikely" were coded as "no" and those that answered "somewhat unlikely" to "very likely" were

recoded as “yes” for presence of SHS in the home. To assess personal smoking history, respondents were asked, “Do you currently smoke, even just once in a while?” (yes/no).

3.2.2.3 Personal Risk Perception

Personal risk perception of lung cancer was assessed by asking participants to, “Rate your risk of developing lung cancer in your lifetime,” on a scale of 0-10 with “0” being lowest risk and “10” highest perceived risk.

3.2.2.4 Emotional Response

Emotional response was assessed by measuring lung cancer worry among participants. Lung cancer worry was assessed using the 4-question Lung Cancer Worry Scale (Butler et al., 2017). Butler et al. (2017) adapted the scale from the 3-item validated Cancer Worry Scale developed by Lerman et al. (1991). The first question is, “How much do you currently worry about getting lung cancer some day?” (5-point Likert scale from (1) not at all to (5) almost all of the time). The remaining questions, “How much do worries about lung cancer impact your mood?” “How much do worries about lung cancer impact your daily activities?” and “When you worry about lung cancer, how difficult is it to control these worries?” were measured on a 4-point Likert scale from (1) not at all to (4) a lot. The first item was multiplied by a factor of 0.8, resulting in a maximum possible value of four to ensure that each of the scale items received equal weight in the total score, representing the sum of the four items. The potential range of scores is 3.8-16, with higher scores indicating greater lung cancer worry. According to Butler et al. (2017), the Lung Cancer Worry Scale has good internal consistency, with a Cronbach alpha coefficient reported of 0.82. In the current study, the Cronbach alpha coefficient for this 4-item scale was 0.79.

3.2.2.5 Synergistic Risk Perception

Synergistic risk perception was assessed by asking participants to "Rate the risk from being exposed to radon AND smoking a pack of cigarettes per day, compared to the risk of only smoking a pack of cigarettes a day with no radon exposure" (5-point Likert scale ranging from (1) "much less risky" to (5) "much more risky").

3.2.2.6 Home Radon Testing

Home radon levels were measured using Radon Safety Services Inc. (RSSI) Alpha-track Radon Detectors, commercially available long-term radon gas detector (Radon Safety Services Inc., 2015). As the radon atoms collect within the detector and decay, microscopic tracks are left within the detector. The average radon level is calculated using the number of tracks made and the number of days the detector was exposed. Participants were asked to deploy their detector for a minimum of 90 days. Radon test kit results were mailed to the principal investigator and then to the participants with a letter explaining the results. As results were received, participants were classified as "yes" for testing. If no results were obtained, participants were classified as "no" for testing. Radon concentrations at or above the Environmental Protection Agency's suggested action level of 4.0 pCi/L were considered high (EPA, 2106a).

3.2.3 Data Analysis

Descriptive statistics using means and standard deviations or frequency distributions were used to summarize study variables. Bivariate analysis, including two-sample t test and chi-square test for independence was used, as appropriate, to compare study variables between those who completed home radon testing and those who did not. Binary logistic regression was used to examine personal risk perception, lung cancer worry, and synergistic risk perception as predictors of home radon testing among rural Appalachia residents, controlling for sociodemographic variables. With the goal of

having at least 10 observations per predictor (Babyak, 2004), the sample size limited the number of predictor variables included in the regression model to five variables. Two sociodemographic variables, including age and income, were included in the regression model based on significant findings from the bivariate analysis and previous research which found an association between age (Halpern & Warner, 1994; Wang et al., 2000), higher income and completion of home radon testing (Halpern & Warner, 1994; Hill et al., 2006; Nissen et al., 2012; Zahnd et al., 2017). The Hosmer-Lemeshow goodness-of-fit test assessed model fit. Preliminary analyses using variance inflation factors were conducted to ensure no multicollinearity was present. All quantitative data analysis was conducted using Statistical Package for the Social Science (SPSS) version 25, with an alpha level of 0.05 throughout.

3.3. Results

3.3.1 Sample Characteristics

Table 3.1 summarizes the sample sociodemographic and personal characteristics by group. The mean age of the entire sample was 46 years (*SD* = 14). The reported mean length in years at their current residence was 11 (*SD* = 10). Overall, most were female (71%), with at least a high school education (86%), married (66%), of White/non-Hispanic decent (86%), and either employed or retired (69%). Forty-one percent reported an income less than $30,000 and 77% reported owning their own home. Half of participants reported the presence of children in the home. The majority of the sample reported living in a smoke-free home (60%) and indicated they did not currently smoke cigarettes (74%). Overall, personal risk perception of lung cancer ratings indicated low perceived risk with an average rating of 3.5 (*SD* = 3.0; range 0-10). Additionally, very

few respondents indicated that they worry much about lung cancer, with an average score of 6 (*SD*= 2.5; range 3.8-13.4). When considering the combination of radon and tobacco smoke, synergistic risk perception scores indicated that the majority of respondents perceived the synergistic risk to be more risky than exposure to tobacco alone without radon exposure (M = 3.6, *SD* = 1.2; range 1-5).

3.3.2 Home Radon Testing and Self-Reported Tobacco Smoke Exposure

Twenty-eight of the 58 (48%) home radon test kits distributed were returned for analysis. Home radon levels for the sample averaged 4.2 pCi/L (*SD* = 4.4). Eight of those who tested (29%) had radon levels at or above the EPA action level of 4.0 pCi/L, with values ranging from 4.7- 19.5 pCi/L. Of the eight with high radon levels, three (38%) reported presence of smoking in the home, no respondents reported being a current smoker.

3.3.3 Bivariate Relationships with Home Radon Testing

Age was the only sociodemographic variable significantly associated with completion of home radon testing (Table 3.1). Compared to those who did not complete home radon testing, participants who tested their homes for radon were older (M = 51 years, *SD* = 11 years versus M = 40, *SD* = 17 years, respectively; $p = .008$). There was no significant difference between the testing groups in length of home residency, sex, education, marital status, race, ethnicity, employment, household income, home ownership, presence of children in the home, or smoking variables. Additionally, there were no significant differences in personal risk perception, lung cancer worry, and synergistic risk perception between those who completed home radon testing and those who did not.

3.3.4 Predictors of Home Radon Testing

The full logistic regression to assess predictors of home radon testing was statistically significant, $x^2(5, N = 48) = 11.1$, $p = .05$, indicating that the model was able to distinguish between those who tested their home for radon and those who did not, based on the variables in the regression. The model as a whole explained 27.6% (Nagelkerke R square) of the variance in home radon testing, and correctly classified 64.6% of cases. The Hosmer-Lemeshow test was not significant ($x^2 = 8.997$, $p = .343$), indicating the model fit the data well. As shown in Table 3.2, age was the only independent variable to make a unique statistically significant contribution to the model, with an odds ratio of 1.080 [CI 1.023-1.140]. For each 1-year increase in age, the odds of testing for radon in the home increased by a factor of 2.2. Therefore, for every 5-year increase in age, participants were 47% more likely to test their home for radon, controlling for other factors in the model. Personal risk perception, lung cancer worry, synergistic risk perception, and income did not make statistically significant contributions to the model in this sample of rural Appalachia Kentucky residents. All variance inflation factors for this model were smaller than 2.052, indicating multicollinearity did not distort regression parameters.

3.4. Discussion

This study sought to compare differences among rural Appalachia residents who completed home radon testing with those who did not, after receiving a free long-term test kit at a rural primary care clinic, and to examine personal risk perception, lung cancer worry, and synergistic risk perception as predictors of home radon testing in a small sample of rural Appalachia residents

Overall, distributing free radon test kits in the primary care setting appears to have prompted many participants to test their homes for radon. Nearly half of study participants tested their home for radon. This is promising as only a total of 65 observed radon values had been documented over a 28-year period from 1986-2014 in the same two study counties (Radon Policy Division, unpubl data). The one-time distribution of free radon test kits in two primary care clinics yielded one-third as many observed radon values as were documented over 28 years in this 2-county area. This finding is consistent with Nissen et al. (2012) and Butler et al. (2018), who reported that availability of free or discounted test kits was associated with completion of home radon testing. In the Nissen et al. (2012) study, participants who indicated they owned their home and had never tested the home for radon were recruited from a primary care office. Those who agreed to follow-up were asked to complete a survey and given a coupon for a reduced cost ($5.95) home radon test kit. Of the 248 coupons distributed, 48 participants ordered a radon test kit, and 36 (14.5%) returned the kits for analysis. In addition, participants were significantly more likely to indicate the availability of a free (38.2% vs. 17.6%, $p = 0.016$) or discounted testing kit and doctor's recommendation (26.5% vs. 2.6%, $p < 0.0001$) as reasons for completing home radon testing at follow-up when compared to baseline. In the Butler et al. (2018) study, participants who received a free test kit on-site were more likely to complete home radon testing than those who were given a coupon for a free test kit which required the participant to call and request a radon test kit be mailed to them. The higher rate of testing found in our study compared to the Nissen et al. (2012) study (48% vs. 14.5%, respectively), and evidence from Butler et al. (2018), provide support for the in-person provision of free test kits in primary care offices.

The two counties evaluated in this study are identified as a Radon Zone 2 by the EPA, indicating that the average indoor radon screening level in the county ranges from 2 to 4 pCi/L (EPA, 1993). However, analysis of the 28 radon test kits returned in this exploratory study indicated that the mean home radon level was 4.2 pCi/L, with eight homes (29%) exceeding the EPA action level of 4.0 pCi/L. The relative lack of radon testing and findings from this study demonstrate the need for more testing in rural Appalachia. These findings highlight the fact that EPA's Radon Zone Map may not be an accurate reflection of radon exposure in this Central Appalachian area. As recommended by the U.S. Surgeon General, every home should be tested in order to determine one's exposure risk (United States Department of Health and Human Services, 2005). Furthermore, test kit findings could be used by clinicians and public health professionals in Appalachia to create teachable moments and prompt action by providing personalized environmental report back (Hahn et al., 2018). The provision of personalized report back may be especially useful given that the majority of participants surveyed reported low perceived personal risk for lung cancer ($M = 3.5$, $SD = 3.0$; range 0-10). McBride et al. (2003) suggests that notification of abnormal test results are optimal teachable moments because the results provide personalized feedback and may increase motivation for action. Lastly, the EPA's Radon Zone Map is intended to help governments and other organizations target communities to receive risk reduction activities and resources (EPA, 1993). With historically high incidence of lung cancer in Appalachia, high prevalence of tobacco use and low home radon testing rates, governments and other organizations need to consider the synergistic effects of radon and tobacco smoke when planning risk reduction activities in regions disproportionately affected by lung cancer.

When comparing those who tested their homes for radon and those who did not, age was the only variable significantly associated with home radon testing. Participants who tested their home for radon were older (M = 51 years vs. M = 40 years, respectively). Similarly, in the model, the only independent predictor for completion of home radon testing was age. As age increased, participants were more likely to test their home for radon, controlling for other factors in the model. Our findings are in contrast to previous studies in which younger age was associated with home radon testing (Halpern & Warner, 1994; Wang et al., 2000). The fact that younger participants in Appalachia were less likely to test their home for radon is of particular concern, potentially exposing individuals and their families to radon in the home for many years. As radon-induced lung cancer risk increases with exposure over time, health professionals need to stress the importance of radon testing and mitigation in this population when discussing primary health promotion strategies, particularly among those who smoke tobacco or are exposed to SHS. Additionally, young adults in the U.S. have significantly lower rates of office-based health care utilization than all other age groups (Lau et al., 2014), demonstrating the need for public health officials to develop novel ways to disseminate primary preventive practices to younger populations.

Contrary to the hypothesis, higher personal risk perception, greater lung cancer worry, and higher synergistic risk perception scores were not associated with testing one's home for radon in the multiple logistic regression. Although the model including these variables was significant overall, none of these factors made a significant contribution individually. One explanation for this finding is that average scores for personal risk perception and lung cancer worry were low in this sample, suggesting

relatively little variability among respondents. This may have been due to the fact that the majority of participants were non-smokers living in smoke-free homes. In previous research, current smokers and those reporting smoking in the home rated their personal risk perception of lung cancer and lung cancer worry significantly higher than non-smokers and those not exposed to SHS in the home (Butler et al., 2017). Without exposure to tobacco, a widely-known lung carcinogen, participants may not have perceived themselves at risk for lung cancer and, therefore, may not have experienced a strong emotional response to the cue to action. Additionally, it is possible that some participants in this study lacked knowledge of the health hazards associated with radon exposure. In Duckworth et al. (2002), 473 participants from rural Illinois were surveyed about their knowledge of radon as a health hazard. While the majority identified radon as a gas, 44% did not know that radon was associated with lung cancer. Furthermore, Hill et al. (2006) found that many rural families underestimate the seriousness of the long-term health effects related to radon exposure, possibly contributing to the lack of perceived personal lung cancer risk and lung cancer worry in this sample. Interventions aimed at assessing radon knowledge and increasing radon risk perception among rural populations are warranted.

In addition, the sample's mean score for synergistic risk perception falls between the perception of equal risk and more risk. As those who are exposed to tobacco smoke and radon have a 10-fold greater risk of developing lung cancer than those not exposed to tobacco smoke, the relatively low mean synergistic risk score is concerning as participants did not perceive the combination of tobacco and radon to be much more risky to one's health than tobacco alone. Numerous studies from around the world have

demonstrated the combined effects of tobacco and radon exposure on lung cancer, with more radon-induced lung cancers occurring among current smokers (Ajrouche, et al., 2018; Bochicchio et al., 2013; Chen et al., 2012; Darby et al., 2005; Grundy et al., 2017; Lee et al., 2015; Menzler et al., 2008; National Research Council, 1999; Peterson et al., 2018; Truta-Popa et al., 2010; Veloso et al., 2012). Perceiving the synergistic risk associated with the combined effects of tobacco and radon as anything but much more risky, indicates a lack of public awareness about the increased risk for lung cancer when exposed to both tobacco smoke and radon. Estimating the number of lung cancer cases attributable to radon exposure at the population level may prompt public health workers to disseminate radon risk reduction strategies and allocate resources based on risk potential. Furthermore, primary care practitioners are well suited to discuss primary prevention strategies with patients and families including home radon testing, mitigation and creating smoke-free homes and vehicles. Educating tobacco users and those who are exposed to tobacco smoke about the combined risks of radon and tobacco exposure may further serve as a cue to action for radon testing.

In contrast to several other studies, sex (Halpern & Warner, 1994), education (Butler et al., 2018; Halpern & Warner, 1994; Nissen et al., 2012; Zahnd et al., 2017), income (Halper & Warner, 1994: Hill et al., 2006; Nissen et al., 2012; Zahnd et al., 2017), home ownership (Hill et al., 2006), nor the presence of children in the home (DiPofi et al., 2001) were associated with home radon testing in this Appalachian sample. Additionally, length of home residency, marital status, race/ethnicity, employment, and smoking variables were also not associated with home radon testing in this Appalachian sample. It is promising that several of the variables which are historically regarded as

determinants of health, i.e., income and educational attainment, did not predict home radon testing. Further research on home radon testing in Appalachia is needed, but findings from this exploratory study indicate that the majority of the population may test their home for radon if home radon test kits are made readily accessible.

3.4.1 Limitations and Strengths

This study has a number of limitations. The small sample size in this exploratory study is the primary limitation, restricting the number of predictor variables that could be included in the logistic regression model. In addition, the convenience sample may have resulted in self-selection bias as participants may have been more motivated to take health actions given they were recruited at a primary care office. Given the sample characteristics, participants were not representative of the rural, low socioeconomic population in the region, as the majority of the sample were homeowners who were non-smokers and lived in smoke-free homes, were employed, and had at least some post-secondary education. Another limitation is that participants' health-related self-concept was not measured. McBride et al. (2003) suggests that having an understanding of how a health event affects each of the three constructs (perception of personal risk and outcome expectancies; affective or emotional response; and health-related self-concept) is important to understanding teachable moments and developing interventions which prompt health behavior change. Having not measured health-related self-concept in this study, researchers were unable to understand its influence on radon testing. In addition, participant knowledge of radon as a risk factor for lung cancer was not assessed, nor were participants asked if their provider counseled them on radon testing. As knowledge of radon and doctor's recommendation have been found to be significantly associated with home radon testing (Duckworth et al., 2002; Nissen et al., 2012; Wang et al., 2000), this

limited the internal validity of our findings. Despite these limitations, the findings from this study provide preliminary evidence of the need for public education about radon and its harmful effects on one's health, particularly when combined with tobacco exposure, in Appalachia Kentucky. In addition, evidence from this study supports the provision of free radon test kits in primary care clinics to promote home radon testing.

3.4.2 Future Implications

While the small sample size does not allow for researchers to generalize the findings, there are areas of concern highlighted in the study findings that have implications for clinical and public health practice. Due to the synergism between tobacco and radon, it is important for all healthcare providers and public health professionals to screen for tobacco exposure and encourage all patients to test their homes for radon, especially those who smoke or report smoking in the home. In this study, providing free, in-person home radon test kits in the primary care office served as a cue to action and may be a promising way to increase radon testing in Appalachia. Lung cancer rates in the region and evidence from this study, necessitate further exploration of the variables associated with radon testing in rural Appalachia. Future studies guided by the TMM which explore radon testing in Appalachia Kentucky need to include a larger, more diverse sample with varying demographics including sex, age, income, education, homeowner versus renter, the presence of children in the home, current smokers, those exposed to SHS, and measurement of health-related self-concept. Additionally, the use of other health behavior theories or models such as the Health Belief Model (Hochbaum, 1958; Rosenstock, 1960), Social Cognitive Theory (Bandura, 1986), and the Theory of Planned Behavior (Ajzen & Fishbein, 1980), to guide research on home radon testing is warranted. Further exploration of theory-driven variables

associated with home radon testing among rural Appalachia residents are needed in order to develop tailored interventions that prompt individuals to take action to reduce radon exposure in the home.

3.5 Conclusions

This exploratory, prospective study was an effort to understand the association between teachable moment variables and radon testing in a rural Appalachian population. While the small sample size makes it difficult to generalize findings, results from this study reveal that the provision of free, in-person home radon test kits as a cue to action in the primary care setting shows promise in increasing radon testing in Appalachia. In addition, younger participants were less likely than older ones to complete home radon testing. This finding is concerning given the cumulative effects of radon exposure on the development of lung cancer. Because there is no safe level of radon exposure, it is important for all healthcare providers to include radon assessment as part of their patient education and encourage all patients to test their homes, especially those who smoke or report smoking in the home. Home radon testing is a primary prevention strategy for the prevention of lung cancer and is an essential step to reducing the burden of disease in Appalachia.

Table 3.1

Sample Characteristics of the Total Sample and by Home Radon Testing Group Using Two-Sample t test or Chi Square Test for Independence

	Total Sample *N*=58	Completed Radon Testing *n* = 28	Did Not Complete Radon Testing *n* = 30	
Characteristic	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	*p*
Age (years)	46 ± 14	51 ± 11	40 ± 17	.008
Length of time at current residence (years)	11 ± 10	12 ± 10	11 ± 10	.626
Personal risk perception	3.5 ± 3.0	3.3 ± 2.9	3.6 ± 3.0	.690
Lung cancer worry	6.0 ± 2.5	6.1 ± 2.7	5.9 ± 2.3	.824
Synergistic risk perception	3.6 ± 1.2	3.7 ± 1.2	3.5 ± 1.3	.493
	n (%)	*n* (%)	*n* (%)	*p*
Sex				
Male	15 (26%)	7 (25%)	8 (27%)	>.99
Female	41 (71%)	21 (75%)	20 (67%)	
Missing data	2 (3%)	0 (0%)	2 (7%)	
Level of education				
< High school	8 (14%)	4 (14%)	4 (13%)	.410[a]
HS graduate/GED	18 (31%)	11 (39%)	7 (23%)	
> High school	32 (55%)	13 (46%)	19 (63%)	
Marital status				
No	18 (31%)	7 (27%)	11 (37%)	.623
Yes	38 (66%)	19 (73%)	19 (63%)	
Missing	2 (3%)	2 (7%)	0 (0%)	
Race and ethnicity				
White and non-Hispanic	50 (86%)	24 (86%)	26 (93%)	.493[a]
Other	2 (3%)	0 (0%)	2 (7%)	
Missing data	6 (10%)	4 (14%)	2 (7%)	
Employment status				
Employed/Retired	40 (69%)	18 (64%)	22 (73%)	.642
Unemployed/Disabled	16 (28%)	9 (32%)	7 (23%)	
Missing data	2 (3%)	1 (4%)	1 (3%)	
Income				
<$30,000	24 (41%)	13 (46%)	11 (37%)	.427
≥$30,000	28 (48%)	11 (39%)	17 (57%)	
Missing	6 (10%)	4 (14%)	2 (7%)	

Table 3.1 (continued)

	Total Sample *N*=58	Completed Radon Testing *n* = 28	Did Not Complete Radon Testing *n* = 30	
Characteristic	*n* (%)	*n* (%)	*n* (%)	*p*
Home ownership				
Own	45 (77%)	23 (82%)	22 (73%)	.441
Rent	12 (21%)	4 (14%)	8 (27%)	
Missing data	1 (2%)	1 (4%)	0 (0%)	
Children present in the home				
No	27 (47%)	15 (54%)	12 (40%)	.292
Yes	29 (50%)	11 (39%)	18 (60%)	
Missing	2 (3%)	2 (7%)	0 (0%)	
SHS in the home				
No	35 (60%)	17 (61%)	18 (60%)	>.99
Yes	23 (40%)	11 (39%)	12 (40%)	
Current smoker				
No	43 (74%)	23 (82%)	20 (67%)	.263
Yes	13 (22%)	4 (14%)	9 (30%)	
Missing	2 (3%)	1 (4%)	1 (3%)	

Note. [a]Fisher's Exact Test used as an alternate to the chi-square test of association due to small expected cell counts

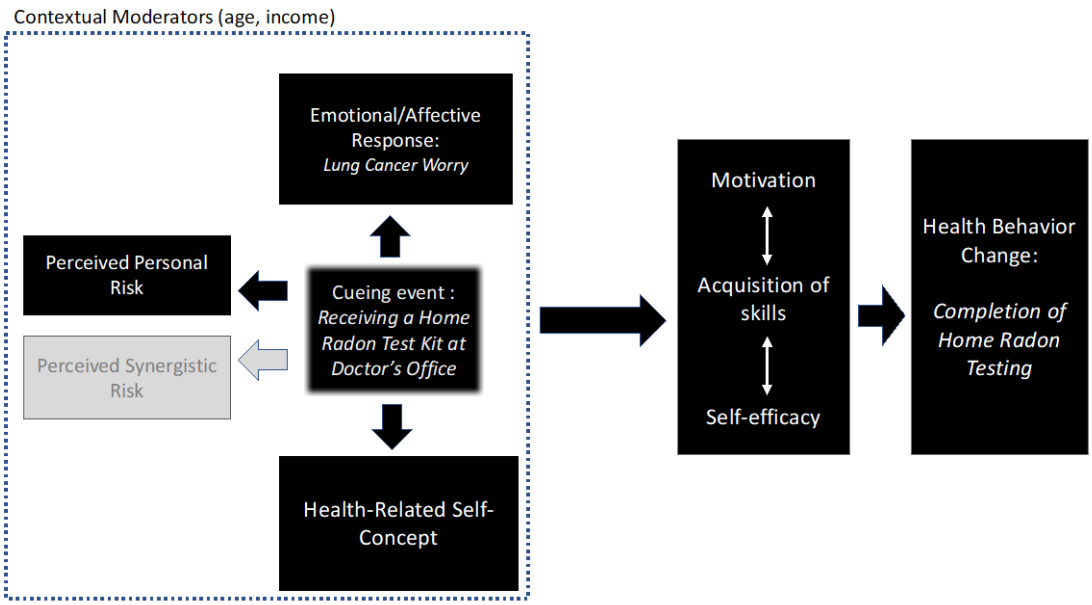
Table 3.2

Logistic Regression Examining the Association Between the Teachable Moment Model Constructs and Completion of Home Radon Testing (n=48)

Variable	*B*	*SE*	*OR*	95% CI	Wald Statistic	*p*
Age (years)	.077	.027	1.080	[1.023-1.140]	7.862	.005
Income	-1.149	.739	.317	[.074-1.350]	2.415	.120
Personal risk perception	-.039	.157	.962	[.707-1.309]	.062	.804
Lung cancer worry	-.035	.193	.966	[.662-1.410]	.032	.858
Synergistic risk perception	.116	.297	1.123	[.627-2.011]	.152	.696

Figure 3.1

Heuristic Model for Teachable Moment



Note. Adapted from McBride et al., 2003. Original constructs are in black.

CHAPTER 4:

SOCIAL DETERMINANTS OF HEALTH, ENVIRONMENTAL EXPOSURES AND HOME RADON TESTING

4.1. Background

Radon is a naturally occurring colorless, odorless, radioactive gas released into the air from the decay of uranium found in rocks and soil. Radon was classified in 1988 as a group 1 carcinogen by the International Agency for Research on Cancer (IARC) after evaluating evidence of carcinogenicity of radon exposure and its decay products in animal and human studies (International Agency for Research on Cancer [IARC], 1988). Since that time, pooled analysis of lung cancer data collected from underground miners by the Committee on the Biological Effects of Ionizing Radiation (National Research Council [NRC], 1999), and case-control studies examining the relationship between residential radon and lung cancer in the general population (Darby et al., 2005; Krewski et al., 2006; Lubin, 2004) have provided additional evidence for the dangers of residential radon exposure and its contribution to the development of lung cancer, including evidence for tobacco and radon synergism, putting those exposed to smoking and radon at greater risk of developing lung cancer (Darby et al., 2005; Krewski et al., 2006; Lubin, 2004; NRC, 1999).

Radon gas is pervasive and found in varying concentrations throughout the world. Yet, exposure to radon occurs largely in the home where we spend the majority of our time, and where concentrations of radon accumulate after the gas enters and becomes trapped (Environmental Protection Agency [EPA], 2016). In the U.S., exposure to radon gas accounts for approximately 15,400-21,800 lung cancer deaths annually, with approximately 13,300-18,900 of those occurring in individuals with a personal history of

smoking (NRC, 1999). While there is no safe level of radon exposure, the EPA and the U.S. Surgeon General have encouraged all Americans to test their homes for radon and take action to reduce the home radon concentration when their levels are at or above 4 picocuries per liter of air (pCi/L) (EPA, 2016; U.S. Department for Health and Human Services, 2005). Home radon testing can be accomplished with the use of do-it-yourself home radon test kits, commonly found at home improvement stores, or by hiring a certified radon measurement professional (EPA, 2016).

Testing one's home for radon is a primary prevention strategy for the prevention of lung cancer and is necessary to determine exposure risk, yet only 3-15% of Americans surveyed have completed home radon testing (Eheman et al., 1996; Wang et al., 2000). Past research has identified social and economic disparities associated with home radon testing including higher income (Halpern & Warner, 1994; Hill et al., 2006; Nissen et al., 2012; Zahnd et al., 2017); higher education (Butler et al., 2018; Halpern & Warner, 1994; Nissen et al., 2012; Zahnd et al., 2017); home ownership (Hill et al., 2006; Wang et al., 2000); and urbanicity (Zahnd et al., 2017). Additionally, social influence (Weinstein et al., 1991; Rinker et al., 2014; Weinstein et al., 1991); and living in a high- risk radon area (Wang et al., 2000; Zahnd et al., 2017) have been known to influence completion of home radon testing.

The U.S. Department for Health and Human Services *Healthy People 2020* (U.S. Department for Health and Human Services [USDHHS], 2010) emphasizes the importance of addressing social and physical determinants of health in order to improve the health of individuals and the communities in which people live (USDHHS, 2010). In *Healthy People 2020,* the Committee set the goal to "create social and physical

environments that promote good health for all" (USDHHS, 2010). The World Health Organization (WHO) defines social determinants of health (SDH) as "the circumstances in which people are born, grow, work, live, and age, and the wider set of forces and systems shaping the conditions of daily life" (World Health Organization [WHO], 2019). It is widely believed that SDH are responsible for the health inequities facing many people around the globe. In 2018, the WHO released The *WHO Housing and Health Guidelines* (2018) which offer evidence-based recommendations for creating healthy housing conditions as a way to address health inequities. The guidelines address numerous aspects of the home environment including exposure to radon (WHO, 2018). The WHO asserts that addressing exposures in the home is especially important in high-income countries, where people spend approximately 70% of their lives inside their homes (Baker et al., 2007; WHO, 2018).

To understand the population-level circumstances in which disparities in home radon testing occur, Zahnd et al. (2017) assessed zip code level variables including EPA radon zone, percent living in poverty, median home value, median household income, percent of the population with at least a high school diploma, percent of owner-occupied homes, and rural/urban location to explore patterns of home radon testing in Illinois. Zahnd et al. (2017) evaluated data from radon tests collected between 2005-2012 by either a licensed radon testing professional or by a do-it-yourself home radon test kit. Overall, living in a high-risk EPA radon zone, median home value, median household income, and percent of the population with at least a high school education were predictive of radon testing, with living in a high-risk EPA radon zone making the greatest contribution (Zahnd et al., 2017). Poverty and living in a rural location were negatively

associated with home radon testing overall (Zahnd et al., 2017). When considering home radon testing by a licensed radon professional, living in a high-risk EPA radon zone had the greatest association with testing, while the percent of the population living in poverty and rurality were negatively associated with home radon testing (Zahnd et al., 2017). In regard to home radon testing using do-it-yourself home radon test kits, living in a high-risk EPA radon zone, median household income, percent of the population with at least a high school education, and percent of owner-occupied homes were positively associated with home radon testing, with owner-occupancy having the greatest association (Zahnd et al., 2017).

Kentucky, a state located in the Southeast portion of the United States, is plagued with health inequity. The majority of the state is considered rural which limits access to employment and health services, and 18.3% of the population live below the poverty level (U.S. Department of Agriculture, 2013; U.S. Census Bureau, 2013-2017). The median household income is one of the lowest in the nation and only 23.2% of the population over the age of 25 have attained a bachelor's degree or higher (U.S. Census Bureau, 2013-2017). Evidence of health inequity is apparent in Kentucky's disease rates. For example, Kentucky leads the nation in incidence and mortality from lung cancer (American Cancer Society, 2020). Much of the state's lung cancer incidence is likely due to tobacco exposure given the high prevalence of smoking (Department for Public Health, Cabinet for Health and Family Services, 2018), lack of smoke-free home rules (King et al., 2013), and lack of smoke-free workplace and public place laws (Kentucky Center for Smoke Free Policy, 2019). However, high radon risk potential is also a contributing factor. In 1993, the EPA developed the "Map of Radon Zones" as a way to

identify areas with the potential for elevated indoor radon concentrations (EPA, 2019a). The EPA "Map of Radon Zones" classifies counties as Zone 1-3 based on their predicted average indoor radon concentrations, with Zone 1 indicating levels greater than 4.0 pCi/L; Zone 2 indicating levels between 2-4.0 pCi/L; and Zone 3 levels less than 2.0 pCi/L (EPA, 1993). In Kentucky, the "Map of Radon Zones" has classified 30 counties as Zone 1, and 82 counties as Zone 2 (EPA, 1993), indicating 93% of Kentucky counties have moderate-to-high radon exposure risk potential.

Despite the increased radon exposure risk potential in Kentucky, fewer than 1% of homes are tested for radon each year (Radon Policy Division unpubl. Data). Additionally, no public policies are in place which mandate home radon testing in Kentucky (Environmental Law Institute, 2018). Given the prevalence of lung cancer, high potential for tobacco and radon synergism, and health inequities throughout Kentucky, the lack of home radon testing across the state is a critical public health concern. As a primary prevention strategy for lung cancer, identification of variables which are predictive of home radon testing in Kentucky is a public health priority and would help guide officials in creating healthy home environments for all. The primary aim of this study was to examine the association between county-level social determinants of health (e.g., median household income, median home value, percent living below poverty level, percent of the population with at least a high school diploma, percent owner-occupied housing, and rural-urban status) and environmental exposures (e.g., radon exposure risk potential, lung cancer incidence rates, and adult smoking prevalence) and rates of home radon testing. It was hypothesized that counties with higher socioeconomic status and radon risk potential would have higher rates of home

radon testing. Lung cancer incidence rate and adult smoking prevalence were included in this study to evaluate their potential to predict home radon testing. It was hypothesized that individuals living in counties with a higher prevalence of lung cancer may perceive themselves as more susceptible to the disease and therefore be more likely to engage in home radon testing. Adult smoking prevalence was included based on findings from a recent study by Butler et al. (2018) in which those who reported living with one or more smokers were 1.5 times more likely to test for radon and secondhand smoke in the home.

4.2. Methods

4.2.1 Design

This was an ecological, descriptive study design using a secondary data analysis of observed radon values from Kentucky homes collected from 1995-2016. A total of 54,683 observed residential radon values were obtained from a statewide radon home testing database that routinely collects radon values from two major radon testing companies serving all 120 Kentucky counties (Radon Policy Division unpubl. data). Each observed residential radon value was aggregated by county in which the measurement was obtained. County-level social determinants of health and environmental exposure variables were obtained from the U.S. Census, U.S. Department of Agriculture, University of Kentucky College of Nursing and Kentucky Geologic Survey Radon Policy Division, Kentucky Behavioral Risk Factor Surveillance System, and the Kentucky Cancer Registry. The study was approved by the University of Kentucky Medical Institutional Review Board.

4.2.2 Measures

Rates of home radon testing were calculated per 10,000 households for each county by dividing the total number of observed radon values by the number of housing units within a county as determined by the 2010 U.S. Census (U.S. Census Bureau, 2010). This value was then multiplied by 10,000 to calculate the annual county-level testing rate per 10,000 households. The annual county-level testing rates were then averaged across the 21 years to get a single average annual testing rate per 10,000 households in each county. Nine population-level variables were assessed in this study. County-level social determinants of health variables including median household income, median home value, percent living below poverty level, percent of the population over the age of 25 with at least a high school diploma, percent owner-occupied housing, and rural-urban status were obtained from the U.S. Census and the U.S. Department of Agriculture. County-level environmental exposure variables including the upper quartile of the distribution of radon values, adult smoking prevalence, and lung cancer incidence rate were obtained from a statewide home radon testing database, the Kentucky Behavioral Risk Factor Surveillance System, and the Kentucky Cancer Registry, respectively. With the exception of adult smoking prevalence and lung cancer incidence rate, variables were chosen based on findings from previous research which explored predictors of home radon testing (Butler et al., 2018; Butterfield & Larsson, 2006; Halpern & Warner, 1994; Hill et al., 2006; Nissen et al., 2012; Weinstein et al, 1991; Zahnd et al., 2017).

4.2.2.1 Social Determinants of Health

Five-year estimates from the U.S. Census Bureau's 2006-2010 American Community Survey (ACS) were used to describe county-level social determinants of

health variables including median household income, median home value, percent living below poverty level, percent of the population 25 years of age and older with high school diploma or higher, and percent owner-occupied housing. The ACS is a product of the United States Census Bureau and consists of an annual survey of demographic, social, economic, and housing characteristics collected from communities across the U.S. (U.S. Census Bureau, 2019). 5-year estimates are produced by the ACS for geographic areas with populations less than 20,000 (U.S. Census Bureau, n.d.). As many counties in Kentucky are rural, ACS data collected over a 5-year period from 2006-2010 were used in this study to provide a more precise multiyear estimate. The 2006-2010 date range was chosen as it falls approximately mid-way between the 1995-2016 timeframe of observed radon values collected from Kentucky homes. The 2003 Rural-Urban Continuum (RUC) Codes from the United States Department of Agriculture were used to assign county level location type (U.S. Department of Agriculture, 2003). County RUC codes are assigned initially by grouping counties as metro or non-metro according to population and work commuting data (U.S. Department of Agriculture, 2019a). Metro counties are then further categorized by the population size of their metro area, and non-metropolitan counties, their degree of urbanization and adjacency to a metro area (U.S. Department of Agriculture, 2019a). RUC Codes have been updated each decennial, with the 2003 RUC Codes utilizing 2000 U.S. population Census data. Each county in the U.S. is assigned a value between 1 and 9, with 1 indicating the most urban and population-dense, and 9 indicating the most rural and least population-dense (U.S. Department of Agriculture, 2019a).

4.2.2.2 Radon Exposure Risk Potential

Perceived community radon risk (Weinstein, Sandman, & Roberts, 1991) and living in a high-risk EPA zone (Wang et al., 2000; Zahnd et al., 2017) have been identified as predictors of radon testing. The 54,683 observed residential radon values collected between 1995-2016 and obtained from the state database were used to determine a value for county-level radon exposure risk potential (Radon Policy Division unpul. data). These residential radon values were obtained from short-term radon test kits and were reported in picocuries per liter of air (pCi/L). Due to the skewed distribution of radon values, the 75th, or upper quartile of the distribution of county-level residential radon values was used to indicate radon exposure risk potential in each county. Given the skewed distribution, the upper quartile of the distribution of county-level residential radon values was seen as a more stable estimate of radon exposure risk potential than the mean (Haneberg et al., 2020).

4.2.2.3 Adult Smoking Prevalence

Adult smoking prevalence by county was collected from the Kentucky Behavioral Risk Factor Surveillance Survey (KY BRFSS) Annual Data Reports. Because the annual number of KY BRFSS participants in less-populated counties often does not meet the threshold for smoking rate estimation, the adult smoking prevalence for each county was calculated as the weighted 3-year average using data from the 2008, 2009, and 2010 KY BRFSS reports. The years 2008-2010 were chosen as they correspond closely with the ACS data. The Behavioral Risk Factor Survey is a product of the U.S. Behavioral Risk Factor Surveillance System (BRFSS). The BRFSS was originally established in 1984 by the Centers for Disease Control and Prevention (CDC) as a way to collect state data on health-related risk behaviors, injuries, select chronic health conditions, and use of preventive services among state residents (Holtzman, 2004). The KY BRFSS survey has

been in place since 1985 (Kentucky Department for Public Health and the Centers for Disease Control and Prevention, 2010). The 2008-2010 KY BRFSS Annual Data Reports are based on a sample of non-institutionalized residents aged 18 years and older in Kentucky (Kentucky Department for Public Health and the Centers for Disease Control and Prevention, 2008; Kentucky Department for Public Health and the Centers for Disease Control and Prevention, 2009; Kentucky Department for Public Health and the Centers for Disease Control and Prevention, 2010).

4.2.2.4 Lung Cancer Incidence Rate

To calculate lung cancer incidence rate in each county, lung cancer incidence cases were obtained from the Kentucky Cancer Registry for 1995 through 2016 (the most complete data available). The KCR is the population-based central cancer registry for the state of Kentucky. Formally established in 1990 by the Kentucky General Assembly, the KCR is funded by the National Cancer Institute's Surveillance Epidemiology and End Results (SEER) program and has been awarded Gold certification annually since 1999 by the North American Association of Central Cancer Registries (NAACCR) for its completeness, accuracy, and timeliness (Kentucky Cancer Registry, 2020). A total of 93,616 lung cancer incidence cases in Kentucky were obtained from the KCR and aggregated by county. For this analysis, incident cases occurring in Kentucky residents aged ≥ 50 years at the time of diagnosis (N= 88,410) and county-level population aged ≥ 50 collected from the 2010 U.S. Census (U.S. Census Bureau, 2010) were used to determine weighted average annual incident lung cancer rates per 10,000 population aged ≥ 50 years for each county. The age cutoff of 50 years was chosen based on literature which examined lung cancer incidence and strength of smoke-free laws in Kentucky and

determined that lung cancer is relatively rare among individuals < 50 years of age in the state (Hahn et al., 2018).

4.2.3 Data Analysis

Descriptive statistics using means, standard deviations, and ranges were used to summarize study variables. The bivariate relationships between social determinants of health (SDH) and environmental exposure variables and annual residential radon testing rate were investigated using Pearson product-moment correlation coefficient. Multiple linear regression was run to assess the association between county-level SDH and environmental exposure variables and rates of residential radon testing in Kentucky. Variance inflation factors assessed whether multicollinearity was present. All data analysis was conducted using Statistical Package for the Social Science (SPSS) version 25, with an alpha level of 0.05 throughout.

4.3. Results

The average county-level aggregate annual residential testing rate was 13.4 per 10,000 households (*SD* = 14.2; Table 4.1) ranging from 2.0 – 98.0 per 10,000 households. The median household income was $37,100 (range = $19,300-$79,400) and median home value was $100,800 (range = $56,300 - $240,000). On average, 16.1% (range = 5.0% - 38.0%) of the population lived below the poverty level; 75.8% (range = 57.0%-91.0%) of those over the age of 25 were at least high school graduates (or equivalent), and 74.3% (range = 57.0% - 88.0%) of homes were occupied by the owner. The mean RUC code was 5.7 (*SD* = 2.8) indicating that most of the counties tended to be lower density, falling between an urban population of 20,000 or more, not adjacent to a metro area, and urban population of 2,500 to 19,999, adjacent to a metro area. The

average upper quartile of the distribution of county-level residential radon values was 5.1 pCi/L (*SD* = 3.4; range = 2.0 – 22.0 pCi/L) and mean county-level aggregate adult smoking rate was 24.2 % (range = 7.0 – 39.0%). The average lung cancer incidence rate per 10,000 individuals aged 50 years and older was 28.9 (range = 18.0-43.0).

Of those predictor variables with significant bivariate associations, percent living below the poverty level, adult smoking prevalence, and lung cancer incidence rate were negatively correlated with annual residential radon testing rates (Table 4.2). The predictor with the strongest bivariate correlation with annual residential radon testing rate was the upper quartile of the distribution of county-level residential radon values (r =.345, p < .001). Percent of owner-occupied housing and rural-urban status were not associated with annual residential radon testing rate.

Due to strong associations among median income, median home value, percent below the poverty level, and percent of adults 25 and older with at least a high school education, as indicated by elevated correlations and variance inflation factors (VIFs), not all could be included in the regression model. Of these, median home value and percent below the poverty level were retained as broad indicators of socioeconomic status, reflecting income and education factors. With only these two socioeconomic variables retained in the model, all VIFs were below 2.861, indicating multicollinearity did not distort regression parameters.

The full linear regression to assess predictors of county-level residential radon testing rates was significant, $F(7, 112) = 6.590$, $p < .001$, $R^2 = .292$ (Table 4.3). County-level median home value, percent living below poverty level, percent owner-occupied housing, RUC code, the upper quartile of the distribution of county-level residential

radon values, adult smoking prevalence, and lung cancer incidence rate explained 29.2% of the variance in home radon testing rates. As shown in Table 4.3, median home value (*b* =.154; *SE(b)* = .060), RUC code (*b* = 1.95; *SE(b)* = .629), and upper quartile of the distribution of radon values (*b* = 1.358; *SE(b)* = .354) each made statistically significant unique contributions to the prediction of home radon testing rates. For each $10,000 increase in median home values, there was a corresponding increase of 1.54 in the annual rate of residential radon testing per 10,000 households. For every 1-unit increase in RUC value (i.e., an increase in county-level rurality), the rate of annual testing per 10,000 households increased by 1.95. For each additional 1 pCi/L of radon exposure risk potential at the county level, annual rates of residential radon testing increased by 1.36 per 10,000 households. Finally, for each 1% increase in county-level adult smoking prevalence, annual rates of residential radon testing per 10,000 households decreased by 0.50.

4.4. Discussion

This study sought to examine the association between county-level measures of social determinants of health, environmental exposures and rates of home radon testing. The following factors each made a unique significant contribution to the prediction of home radon testing: median home value, RUC code, the upper quartile of the distribution of radon values, and adult smoking prevalence.

Similar to Zahnd et al. (2017), median home value was a significant predictor of county-level rates of home radon testing in our study. As county-level median home value increased, county-level rates of home radon testing also increased. Additionally, county-level median home value was strongly, positively correlated with county-level

median household income and percent of the population over the age of 25 with at least a high school diploma, indicating increasing home value may be an indicator of greater affluence. As quality of housing has implications for people's health, these findings are concerning and demonstrate the potential inequities in home air quality between those with greater affluence and those without. As counties of lower affluence carry a greater burden of cancer mortality (Ward et al., 2004), radon risk reduction messages and programs aimed at reaching low income populations are needed. Those of low income and low educational attainment are also more likely to engage in use of tobacco products (CDC, 2019) which raises concern for tobacco and radon synergism in the less-affluent population. The World Health Organization (2018) suggests that national radon programs work in collaboration with those working in tobacco control to raise public awareness about the health risks associated with radon exposure.

In contrast to the hypothesis and the study by Zahnd et al. (2017) in Illinois, we found rates of home radon testing escalated as rurality increased. The level of analysis in the Zahnd (2017) study was zip code and they utilized Rural-Urban Commuting Area (RUCA) codes from the U.S. Department of Agriculture to determine zip code-level rurality. RUCA codes are used to classify U.S. census tracts using measures of urbanization, population density, and daily commuting (U.S. Department of Agriculture, 2019b). Tracts are assigned a value between 1 and 10, with 1 indicating the most urban and population dense and 10 indicating the most rural and least population dense (U.S. Department of Agriculture, 2019b). In Zahnd et al. (2017), investigators designated zip codes as either rural or urban by dichotomizing RUCA codes 1 to 3 as urban, and codes 4 to 10 as rural. In contrast, we considered the range of RUC codes from 1 to 9 to measure

urbanicity and rurality in each Kentucky county. County-level rates of home radon testing were calculated per 10,000 households in each county and is therefore a function of the underlying population. It is possible that home radon testing rates in rural counties were found to be higher than in more urban areas of the state due to the distribution of the population. Regardless, the mean annual home radon testing rate for the state was low at 13.4 per 10,000 households and demonstrates the need for promotion of home radon testing throughout the state.

The upper quartile of the distribution of county-level residential radon values demonstrated the strongest, albeit modest, positive correlation with annual residential radon testing rate. As county-level radon risk potential increased, so did residential radon testing rates. This finding is similar research by Wang et al. (2000) and Zahnd et al. (2017). Wang et al. (2000) surveyed 993 New York state residents who were knowledgeable of radon and found a higher proportion of respondents living in radon Zone 1 had completed home radon testing in comparison to Zone 2 and Zone 3. Zahnd et al. (2017) investigated patterns of home radon testing by either a do-it-yourself home radon test kit or by licensed professionals in Illinois and found Illinois zip codes designated as EPA Zone 1 to have higher rate ratios of home radon testing overall than zip codes designated as EPA Zone 2 and 3. Living in a high-risk EPA Zone was positively associated with home radon testing and was a significant predictor of home radon testing overall (Zahnd et al., 2017).

While not explored in our study, it is possible that those living in counties with higher radon risk potential may have heightened perception of community radon risk and be influenced by others in the community. Rinker et al. (2014) surveyed 129 homeowners

and found that those who knew others who had tested their home for radon were seven times more likely to plan to test their own home. Given that there is no safe level of radon exposure and radon concentrations are known to vary within counties, use of geologically-based radon potential maps which account for observed radon values and known geologic formation (Hahn et al., 2015) could serve as better public communication tools of community radon risk potential than the EPA's "Map of Radon Zones." Use of geologically-based radon potential maps to inform the public may heighten perceived community radon risk and lead to increased home radon testing. Further investigation into the impact of social influence on radon testing is warranted and may be particularly helpful in counties with lower radon testing rates.

This study was the first to assess adult smoking prevalence as a county-level predictor of home radon testing, and the findings are not surprising given that smokers often do not engage in preventive health behaviors (Zhang et al., 2017). We discovered a moderate, negative correlation between adult smoking prevalence and rates of home radon testing and linear regression demonstrated adult smoking prevalence was negatively associated with rates of home radon testing. As county-level adult smoking prevalence increased, rates of home radon testing decreased. The lack of home radon testing among high smoking prevalence populations is concerning, particularly given the synergism between smoking and radon-induced lung cancer. Those exposed to tobacco and radon have a 10-fold greater risk of developing lung cancer than non-smokers and those not exposed to secondhand smoke (EPA, 2019b). While there is little research on the topic of smoking and home radon testing, recent research suggests that those exposed to secondhand smoke in the home may be as likely to test for radon (Hahn et al., 2017).

In an exploratory study of 47 renters, half with smokers in the home and half without, participants were provided with free test kits for radon and air nicotine and asked to test their home (Hahn et al., 2017). Those with one or more smokers in the home were as likely as those living without smokers in the home to test for radon and secondhand smoke (Hahn et al., 2017). It was suggested by investigators that the availability of the free home radon test kit may have led to the high testing rate in the study (Hahn et al., 2017). Other studies have demonstrated that ready access to low-cost (Nissen et al., 2012) and free (Butler et al., 2018) home radon test kits in primary care offices positively influences home radon testing. Removing barriers to testing by having home radon test kits readily accessible in physician offices may be one method to increase home radon testing among smokers and those exposed to secondhand smoke.

In contrast to the hypothesis, higher county-level rates of lung cancer incidence were not associated with higher county-level rates of home radon testing. While not statistically significant, this finding is concerning and has practice implications. As physician recommendation has been shown to increase home radon testing (Nissen et al., 2012), delivering radon education to healthcare providers in counties with high smoking prevalence and lung cancer incidence is needed in order to influence provider recommendation leading to an increase in home radon testing.

4.4.1 Limitations and Strengths

Limitations are inherent in the use of population-level data. As Kentucky is composed of 120 counties and the majority of them are considered rural, annual rates of home radon testing and lung cancer incidence cannot be reliably calculated using single-year data estimates due to too few or no occurrences of radon testing or lung cancer cases. Therefore, the 21-year time period of radon testing and lung cancer incidence was

used to in order to calculate stable rates of each. As a result, we were not able to evaluate any changes over time in either testing rates or lung cancer rates. Studies in more populous areas where testing may be more prevalent would benefit from the ability to consider the effect of time on these relationships. Additionally, KY BRFSS and ACS data are self-report and may be subject to under- or over-reporting. For example, as stigma may be associated with self-report of smoking, participants may under report their tobacco use. Furthermore, the KY BRFSS is a telephone survey, so those living in homes without a telephone are not represented in the data. Furthermore, as approximately 70% of counties in Kentucky are rural according to RUC codes, it is possible that rurality as a predictor of home radon testing, may be due in part, to the skewed distribution of rural RUC codes in the state and the underlying distribution of the population. Lastly, as population-level data were used, individual-level conclusions cannot be drawn. Further research is needed to determine if relationships identified in this study using population-level data translates to the individual-level.

Although we did use every available test result from the 21-year period, we acknowledge that not all tests were captured within our data. For example, residential radon testing by licensed radon measurement and mitigation professionals was not included in the statewide home radon testing data base used for this study. As a result, the upper quartile measurements used in this analysis may have been underestimated.

Despite the limitations, this study had several strengths. In Wang et al. (2000) and Zahnd et al. (2017), radon risk potential was evaluated using the EPA Radon Zone maps. In Kentucky, the EPA Radon Zone maps demonstrate little variability in risk potential across counties as 93% are designated moderate-to-high radon exposure risk potential

(EPA, 2003). However, radon exposure risk potential has been known to vary considerably within counties (Hahn, et al., 2015). Therefore, the use of observed radon values gathered from the state radon database to estimate the upper quartile of the distribution of radon values is seen as a more accurate measure of county-level radon risk potential and is a strength in this study. Additionally, the use of interval level measure of location (e.g., RUC Codes 1-9), as opposed to dichotomizing values into urban/rural is a strength in this study. Had we dichotomized RUC codes into urban/rural, as was done in Zahnd et al. (2017), we would have lost the variability in urbanicity/rurality as there are multiple Kentucky counties within each RUC category. Combining the RUC categories into only two groups (urban/rural) would result in a loss of information as 6 of the 9 categories would be collapsed into one and designated as rural.

4.5 Conclusions

Given that there is no safe level of radon exposure, and radon concentrations are known to vary from home-to-home, the elevated radon risk potential throughout Kentucky indicates that much of the population is at risk for radon-induced lung cancer. Additionally, the high adult smoking prevalence means many Kentuckians are potentially at risk for experiencing the devastating synergistic effects of tobacco and radon exposure. The findings from this study have implications for public health interventions and policy development. As we work to create healthy home environments for all, efforts to increase home radon testing, particularly among smokers and those exposed to secondhand smoke in the home, are needed. By identifying the county-level predictors of home radon testing rates, public health officials can target interventions to address the disparities in home radon testing. Counties with low median home values and high prevalence of adult

smoking may benefit the most from public health interventions. Enactment of public policies which address radon during real estate transactions, rental agreements, and in new home construction are warranted (Environmental Law Institute, 2012). As the state leads the nation in incidence and mortality from lung cancer, public health efforts are critically needed to promote the creation of both radon- and smoke-free homes.

Table 4.1

County-Level Social Determinants of Health and Environmental Exposure Characteristics (N=120)

Characteristic	Mean ± *SD* [Range]
Annual residential radon testing rate (per 10,000 households)	13.4 ± 14.2 [2-98]
Social Determinants of Health Variables	
County median household income (thousands of dollars)	37.1 ± 10.0[19.3-79.4]
County median home value (thousands of dollars)	100.8 ± 31.8 [56.3-240.0]
% living below poverty level	16.1 ± 6.5 [5.0-38.0]
% of the populations with at least a high school diploma	75.8 ± 7.8 [57.0-91.0]
% owner-occupied housing	74.3 ± 5.8 [57.0-88.0]
Rural-Urban Continuum Code	5.7 ± 2.8 [1-9]
Environmental Exposure Variables	
Upper quartile of radon (pCi/L)	5.1 ± 3.4 [2.0–22.0]
Adult smoking prevalence, average yearly aggregate	24.2 ± 5.7 [7.0–39.0]
Lung cancer incidence rate (per 10,000 aged ≥ 50 years)	28.9 ± 5.2 [18.0-43.0]

Note. SD, standard deviation. Annual radon testing rate and lung cancer incidence rate, 1995-2016. Rural-Urban Continuum Code 2003. Adult smoking prevalence, 2008-2010. All other variables 2006-2010.

Table 4.2

Pearson Product-moment Correlations between County-level Annual Residential Radon Testing Rates, Social Determinants of Health, and Environmental Exposure Variables

Measure	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Annual residential radon testing rate (per 10,000 households)	*1.00*									
Median household income, thousands of dollars	*.274^*	*1.00*								
Median home value, thousands of dollars	*.323^*	*.877^*	*1.00*							
% living below poverty level	*-.279^*	*-.834^*	*-.619^*	*1.00*						
% of the population over the age of 25 with at least a high school diploma	*.304^*	*.865^*	*.748^*	*-.869^*	*1.00*					
% owner-occupied housing	*-.058*	*-.066*	*-.266^*	*-.046*	*-.222**	*1.00*				
Rural-Urban Continuum Code	*-.093*	*-.717^*	*-.723^*	*.562^*	*-.664^*	*.289^*	*1.00*			
Upper quartile of the distribution of radon values (pCi/L)	*.345^*	*.187**	*.280^*	*-.110*	*.188**	*-.198**	*-.275^*	*1.00*		
Adult smoking prevalence, average yearly aggregate	*-.330^*	*-.456^*	*-.401^*	*.501^*	*-.569^*	*.054*	*.275^*	*-.078*	*1.00*	

Table 4.2 (continued)

Measure	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Lung cancer incidence rate, (per 10,000 aged ≥ 50 years)	*-.246^*	*-.602^*	*-.565^*	*.601^*	*-.609^*	*-.035*	*.422*	*-.241^*	*.381*	*1.00*

Note. * *p* <.05, ^ *p* <.01

Table 4.3

Summary of Multiple Linear Regression Assessing County-Level Predictors of Home Radon Testing Rates (N=120)

Regressor	Estimated *b(SE)*	Standardized Estimated *b*	*p*-value
County median home value, thousands of dollars	.154 (.060)	.345	.012*
% living below poverty level	-.366 (.272)	-.168	.181
% owner-occupied housing	-.015 (.218)	-.006	.946
Rural-Urban Continuum Code	1.947 (.297)	.379	.002*
Upper quartile of radon (pCi/L)	1.358 (.354)	.328	.000*
Adult smoking prevalence, average yearly aggregate	-.501 (.234)	-.202	.035*
Lung cancer incidence rate	.126 (.295)	.046	.669

Note. *p < .05 indicates significance. Rural-Urban Continuum Code 2003; Adult smoking prevalence, 2008-2010; Lung cancer incidence 1995-2016; All other variables 2006-2010.

CHAPTER 5:

DISSERTATION SYNTHESIS OF FINDINGS, DISCUSSION, IMPLICATIONS, AND CONCLUSIONS

5.1. Background and Purpose

Despite being recognized as a carcinogen over 30 years ago by the International Agency for Research on cancer (World Health Organization [WHO], 1998), radon gas continues to be a major threat to public health. In the U.S., lung cancer remains the leading cause of cancer mortality in men and women (American Cancer Society [ACS], 2020), yet the disease remains highly preventable. While tobacco use is the leading cause of lung cancer, miner cohort and case-control residential studies from around the world provide sufficient evidence to assert exposure to radon as a leading cause of lung cancer. In addition, evidence suggests that those exposed to both radon and tobacco smoke are at an even greater risk for developing lung cancer (National Research Council, 1999).

Testing one's home for radon is a primary prevention strategy to reduce lung cancer, yet the proportion of Americans who have completed home radon testing remains low (Eheman et al., 1996; Wang et al., 2000). In Kentucky, evidence indicates fewer than 1% of homes test for radon annually (Radon Policy Division unpubl. data). Additionally, many Kentuckians are exposed to tobacco smoke through either personal use, in their home, or at indoor work and public places, raising concern about the effects of tobacco and radon synergism on the population. Public policies to strengthen tobacco and radon control have been suggested, yet home radon testing in Kentucky remains voluntary and there are no laws in place to mandate radon control in new construction, nor in rental properties. Additionally, only approximately one-third (36%) of Kentuckians are

protected by smoke-free policies covering all indoor work and public places (Kentucky Center for Smoke Free Policy, 2019).

As the nation's leader in incidence and mortality from lung cancer, Kentucky would benefit from further studies of the population attributable risk of radon exposure on lung cancer and results could be used to inform radon control policies, healthcare practices, and health promotion. Additionally, identification of predictors of home radon testing would assist public health workers target those in the population who would benefit the most from radon control interventions.

The purpose of the dissertation was to: 1) review the literature on methods utilized to quantify population attributable risk of residential radon exposure on the development of lung cancer; 2) explore predictors of home radon testing in rural Appalachia; and 3) examine the association between county-level social determinants of health, environmental exposures and rates of home radon testing. Despite the limitations of each manuscript, this dissertation contributes to the body of research on population attributable risk of radon induced lung cancer and residential radon testing as a means of lung cancer prevention.

5.2. Synthesis of Findings

5.2.1 Chapter 2: Attributable Risk of Radon-induced Lung Cancer: A Systematic Review

The purpose of the first manuscript was to: (a) identify recent studies that have assessed the proportion of lung cancer that can be attributed to residential radon exposure; (b) describe the variables and methods utilized to quantify population attributable risk (PAR) and number of radon-induced lung cancers, taking into account smoking status and sex; and (c) examine the potential effects of radon mitigation on

reductions in population radon exposure-related mortality. A systematic review of the literature using PubMed was employed using the key phrases radon AND attributable risk; lung cancer AND attributable risk; radon AND attributable fraction; lung AND attributable fraction; radon AND population attributable risk. Nine articles published between 2008 and 2018 met inclusion criteria and were retained for analysis. Methods used to calculate excess relative risk and the variables used to determine PAR varied.

The nine studies utilized descriptive epidemiologic designs to determine population attributable risk of radon-induced lung cancer. Studies were conducted in Italy (Bochicchio et al., 2013); Portugal (Veloso et al., 2011); Romania (Truta-Popa et al., 2010; France (Ajrouche et al., 2018); Germany (Menzler et al., 2008); Switzerland (Menzler et al., 2008); Canada (Chen et al., 2012; Grundy et al., 2017; Peterson et al., 2013); and Korea (Lee et al., 2015). Four models were used to calculate excess relative risk included the BEIR-VI exposure-age-concentration (EAC); BEIR-VI exposure-age-duration (EAD); European Pooling; and the Environmental Protection Agency (EPA) model. All estimates of PAR were calculated using lung cancer mortality data. In all but one study, observed radon values were collected from nationally representative surveys. Correction for radon measurement uncertainties was variable and smoking data included either smoking prevalence or an estimate of the number of lung cancers attributable to smoking.

Overall, PAR estimates were highest using the EAC model and lowest using the European Pooling Model with lung cancer mortality attributable to radon ranging from 231 to approximately 3,366 deaths annually. Estimates indicate exposure to radon is a leading cause of lung cancer deaths among never-smokers. Due to the higher absolute

risk of lung cancer from the combined effects of smoking and radon, ever-smokers most often incurred a greater number of deaths due to residential radon exposure than never-smokers. A greater number of radon-induced lung cancer deaths occurred among men as a result of higher prevalence of smoking and relative risk. Exploration of the effects of radon mitigation on attributable risk of radon-induced lung cancer was associated with decreased lung cancer mortality. Uncertainties in estimates stemmed from the approximation of indoor radon concentrations and smoking prevalence in the population, and from the use of the two BEIR-VI models which extrapolated results from studies of miners to assess lung cancer risk in the general population.

5.2.2 Chapter 3. Predictors of Home Radon Testing in Rural Appalachian Kentucky

The purpose of the second manuscript was to: 1) compare differences in sociodemographic characteristics, personal risk perception of lung cancer, lung cancer worry, and synergistic risk perception among rural Appalachia residents who completed home radon testing with those who did not, after receiving a free long-term test kit at a rural primary care clinic; and 2) examine the association between the Teachable Moment Model constructs of personal risk perception, emotional response, and synergistic risk perception and home radon testing in a small sample of rural Appalachian residents.

The Teachable Moment Model (TMM) (McBride et al., 2003) was selected as the theoretical framework in order to provide insight into how teachable moments could promote residential radon testing in Appalachia Kentucky. The TMM suggests that individuals are more likely to take action when they experience a health event that causes them to reflect upon their beliefs and knowledge about their own health, increases their perception of personal risk, and creates a strong affective or emotional response

(McBride et al., 2003). In addition, this subjective assessment of health events may be influenced by an individual's sociodemographic characteristics (McBride et al., 2003). Multiple logistic regression was used to determine demographic and personal characteristics associated with home radon testing among a convenience sample of 58 participants aged 18 years and older who were recruited from their primary care office and provided with a free long-term home radon test kit. Of the 58 test kits distributed, 28 (48%) were deployed and returned for analysis. Overall, the model including age, income, personal risk perception, lung cancer worry, and synergistic risk perception was significant indicating that the model was able to distinguish between those who tested their home for radon and those who did not. Age was the only independent variable to make a significant unique contribution to the model; for every 5-year increase in age, participants were 47% more likely to test their home for radon. Providing free home radon test kits as a cue to action in the primary care setting shows promise in prompting radon testing in Appalachia. However, as radon-induced lung cancer risk increases with exposure over time, efforts are warranted to encourage testing among younger individuals. Given the historically high incidence of lung cancer, high prevalence of tobacco use, and low home radon testing rates in the region, additional research utilizing a larger sample is needed to further explore predictors of home radon testing.

5.2.3 Chapter 4. Social Determinants of Health, Environmental Exposures and Home Radon Testing

The purpose of the third manuscript was to examine the association between county-level social determinants of health (e.g., median household income, median home value, percent living below poverty level, percent of the population with at least a high school diploma, percent owner-occupied housing, and rural-urban status), environmental

exposures (e.g., radon exposure risk potential, lung cancer incidence rates, and adult smoking prevalence) and rates of home radon testing.

The average county-level aggregate annual residential testing rate was 13.4 per 10,000 households. The upper quartile of the distribution of county-level residential radon values had the strongest, albeit modest, positive correlation with annual residential radon testing rate. Percent living below the poverty level, adult smoking prevalence, and lung cancer incidence rate were negatively correlated with annual residential radon testing rates. The multiple linear regression to assess predictors of county-level residential radon testing rates was significant overall. County-level median home value, rural-urban status, upper quartile of the distribution of radon values, and adult smoking prevalence each made statistically significant unique contributions to the prediction of home radon testing rates. For each $10,000 increase in median home values, there was a corresponding increase of 1.54 in the annual rate of residential radon testing per 10,000 households. For every 1-unit increase in RUC value (i.e., an increase in county-level rurality), the rate of annual testing per 10,000 households increased by 1.95. For each additional 1 pCi/L of radon exposure risk potential at the county level, annual rates of residential radon testing increased by 1.36 per 10,000 households. Finally, for each 1% increase in county-level adult smoking prevalence, annual rates of residential radon testing per 10,000 households decreased by 0.50.

Consideration of social determinants of health and environmental exposures are warranted when designing public health interventions to increase home radon testing in order to create healthy home environments for all. Given the synergism between smoking and radon exposure, counties with low median home values and high prevalence of adult

smoking would benefit the most from radon and tobacco control public health interventions.

5.3. Limitations and Strengths

This dissertation has several limitations. To begin, the second and fourth chapters utilized descriptive epidemiologic methods and assessed population-level demographic data and environmental exposure. While the use of population-level epidemiologic data and methods contribute to the understanding of how social and economic circumstances and environmental exposures influence home radon testing, individual-level conclusions cannot be drawn. Further research is needed to determine whether findings are substantiated at the individual level. Additionally, in Chapter Four, the full 21-year time period of radon testing and lung cancer incidence was used to in order to calculate stable rates of each. As a result, I was not able to evaluate any changes over time in either testing rates or lung cancer rates. In Chapter Three, the sample size utilized to explore predictors of home radon testing in rural Appalachia was small and convenience sampling may have led to self-selection bias. Further research in the region is needed to validate findings. Additionally, participants' health-related self-concept was not measured, limiting our understanding of how the distribution of free radon test kits in the primary care office may serve as a teachable moment and influence completion of home radon testing in rural Appalachia Kentucky.

Despite the limitations noted, this dissertation has a number of strengths. To begin, to the author's knowledge, a systematic review of the literature on the PAR of radon-induced lung cancer which critically examines the methods and variables used to calculate the PAR has not yet been attempted. Findings from the systematic review of the

literature provide valuable insight for those seeking to understand PAR of radon-induced lung cancer and those seeking to calculate PAR of radon-induced lung cancer in a population. Additionally, the one-time distribution of free radon test kits in two primary care clinics served as a cue to action and yielded one-third as many observed radon values as were documented over 28 years in the 2-county area. This finding provides support for the in-person provision of free test kits in primary care offices and may be a promising way to increase home radon testing in Appalachia. Additionally, previous studies have used the EPA Radon Zone maps to indicate county-level radon risk potential. As the EPA Radon Zone maps indicate little variability in radon risk potential across Kentucky, the use of observed radon values gathered from the state radon database to estimate the county-level upper quartile of the distribution of radon values, is seen as a more accurate measure of county-level radon risk potential and is a strength in this dissertation.

5.4. Future Implications

5.4.1 Research

The systematic review of the literature highlights the complexity of determining PAR of radon-induced lung cancer. As with any descriptive epidemiologic study, the use of data from representative samples are ideal. In order to inform the development of public policy in Kentucky, well designed case-control studies using residential radon measurements would add to the science and provide further evidence for the use of a residential radon model (e.g., European Pooling Model) over models developed from studies of miners. To minimize uncertainties, utilization of observed residential radon concentrations at the finest geographical level, collected using long-term testing methods,

and corrected for season and measured floor of the home is warranted in future studies. Consideration of the combined use of known geologic rock formation and observed radon values may increase the accuracy of residential radon exposure estimates (Hahn et al., 2015). As many in Kentucky are exposed to secondhand smoke in their homes, worksites and public places, determination of the PAR of radon-induced lung cancer among those also exposed to secondhand smoke may further inform radon- and tobacco-control policies. Additionally, in order to capture the true total number of lung cancers attributable to radon exposure, lung cancer incidence data from the Kentucky Cancer Registry, as opposed to mortality data, is warranted.

The exploration of predictors of home radon testing in rural Appalachia revealed findings in contrast to other studies. I found that older, not younger aged populations (Halpern & Warner, 1994; Wang et al., 2000), were more likely to test for radon. Given the knowledge that radon-induced lung cancer risk increases with exposure over time, further research with a larger sample that is representative of the population found within the region is needed to determine if this finding holds true for a larger rural Appalachia population. If so, novel ways to promote radon testing with younger populations in Appalachia Kentucky are needed. As female sex (Halpern & Warner, 1994), presence of children in the home (DiPofi et al., 2001) and strong provider recommendation (Nissen et al., 2012) have been associated with completion of home radon testing, one such way may be a partnership with healthcare practices which provide care to pregnant women and pediatrics. In Hahn et al. (2014), parents and caregivers were recruited from a pediatric office to assess the feasibility and impact of a radon and secondhand smoke screening and environmental feedback intervention and examine changes in measured

perceived risk of lung cancer and synergistic risk perception. Investigators found participants were receptive to messages which emphasized their children's health and safety and parents reported a greater perceived risk of lung cancer and synergistic risk following the intervention (Hahn et al., 2014). Additionally, low mean scores for personal risk perception, lung cancer worry, and synergistic risk perception in our study indicate the need for public education and messaging research using teachable moments as a way to prompt behavior change. To understand its contribution to the Teachable Moments Model and guide the development of interventions aimed at promoting home radon testing, health-related self-concept needs to be measured in future studies.

In Chapter 4, the use of county-level data to examine the association between social determinants of health and environmental exposures and rates of home radon testing limits our ability to draw individual-level conclusions. Therefore, further research is needed to determine if the relationships identified in this study translate to the individual-level. Additionally, the 21-year time period of radon testing and lung cancer incidence was used in order to calculate stable rates of each. As a result, we were unable to evaluate any changes over time in either testing rates or lung cancer rates. Future studies using data collected from more populous areas where testing may be more prevalent, would benefit from the ability to consider the effect of time on these relationships.

5.4.2 Practice

Findings from Chapter 3 reveal that the provision of free, in-person home radon test kits may be a cue to action in the primary care setting, showing promise in increasing radon testing in Appalachia. Additionally, average scores for personal risk perception and lung cancer worry were low in the convenience sample despite the fact that 29% of those

who tested their homes had home radon concentrations equal to or exceeding the EPA action level of 4.0 pCi/L. These findings suggest the need for public health interventions to increase radon awareness and testing in the region. One way to achieve this may be through a partnership with real estate agents and home inspectors in the region. A recent multi-state study which sought to measure radon knowledge among homebuyers (N = 995), found real estate agents (69%) and home inspectors (65%) to be the most common sources of radon information (Neri et al., 2018). Additionally, homebuyers who reported having discussed radon with a real estate agent were significantly more likely to have tested for radon (Neri et al., 2018).

The examination of the association between county-level social determinants of health, environmental exposures and rates of home radon testing revealed a moderately strong, negative correlation between county-level adult smoking prevalence and annual residential radon testing rates. Due to the synergism between tobacco and radon, it is important for all healthcare providers and public health professionals to screen for tobacco exposure and encourage all patients to test their homes for radon, especially those who smoke or report smoking in the home. While healthcare practitioners need to advise all individuals to test their home for radon, findings from Chapter 4 indicate that if we are to create healthy home environments for all, special consideration should be given to promote home radon testing in counties with lower observed radon values, those of less affluence, and those with high prevalence of adult smoking.

5.4.3 Policy

Given the disparities in smoking prevalence and lack of home radon testing, calculation of the population attributable risk of radon induced lung cancer in Kentucky may be useful to public health officials, lawmakers, and the state radon program.

Quantification of the number of lives saved through radon mitigation could provide further evidence for the development of public policies and accessible, affordable programs aimed at reducing smoking and radon concentrations in homes. Furthermore, as a means of increasing radon awareness and home radon testing, creation of public policies which addresses radon during real estate transactions, rental agreements, and in new home construction are warranted. For example, the *Illinois Radon Awareness Act of 2008* mandates the provision known radon testing results and a general radon disclosure warning statement to the home buyer. The statement encourages home buyers to perform a radon test prior to purchase or taking occupancy of the home, and mitigate if elevated levels are found. Additionally, the Act mandates elevated concentrations of radon in rental property be disclosed to a potential lessee when known (Illinois Compiled Statues, 2008). Since the Act took effect in 2008, Illinois has experienced a more than 45% increase in radon testing during real estate transactions (American Lung Association, 2018).

5.5. Conclusion

In summary, this dissertation adds to the body of research involving attributable risk of radon-induced lung cancer and residential radon testing as a means of lung cancer prevention. Findings from this dissertation can be used to inform researchers, healthcare providers, public health officials, and lawmakers on the potential dangers of radon exposure, particularly among those also exposed to tobacco smoke, as well as individual and population-level predictors of home radon testing. Such information can then be used to guide the development, implementation, and evaluation of public health initiatives and

policies which aim to increase radon testing and mitigation and subsequently reduce the burden of lung cancer.

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Chapter Five

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Place of Birth: Cincinnati, OH
Education:

Institution	Degree	Date	Field of Study
University of Louisville	MSN	2009	Oncology Clinical Nurse Specialist
University of Kentucky	BSN	2001	Nursing

Professional Experience:

Dates	Institution and Location	Position
03/2011 -Present	Baptist Health Lexington Lexington, KY	Oncology Clinical Nurse Specialist
01/2016- 05/2016	University of Kentucky College of Nursing Lexington, KY	Research Assistant- BREATHE Team
08/2009- 03/2011	University of Kentucky Medical Center-Outpatient Oncology Lexington, KY	Staff Nurse
06/2009- 08-2009	Ephraim McDowell Regional Medical Center Danville, KY	Oncology Clinical Nurse Specialist
05/2006- 05/2009	University of Kentucky Medical Center, Blood and Marrow Transplant Unit Lexington, KY	Staff Nurse
08/2007- 12/2007	Midway College Midway, KY	Clinical Instructor
05/2005- 05/2006	University of Kentucky Medical Center, Outpatient Oncology Lexington, KY	Staff Nurse
07/2004- 05/2005	American Mobile Healthcare	Travel Nurse

Dates	Institution and Location	Position
02/2002-07/2004	University of Kentucky Medical Center, Blood and Marrow Transplant Unit Lexington, KY	Staff Nurse

HONORS/AWARDS/GRANTS

2019 Dorothy Luther Fellowship Fund Award
University of Kentucky College of Nursing

2019 CARERC Scholar- traineeship
University of Kentucky College of Nursing

2018 CARERC Scholar- travel scholarship
University of Kentucky College of Nursing

GNAAC Travel Award
University of Kentucky College of Nursing
February 2018

2017 Sima Rinku Maiti Memorial Scholarship
University of Kentucky College of Nursing

2016 & 2017 Betsy M. Holliday and Eunice S. Milton Scholarship
University of Kentucky College of Nursing

2015 ONS Foundation Research Doctoral Scholarship
Oncology Nursing Society Foundation

2014 ONCC Roberta Scofield Award Winner
Oncology Nursing Certification Corporation

Nursing Professional Advancement Award
University of Kentucky Medical Center
May 2009

Publications:

Stanifer, S.R. & Hahn, E.J. (in press). Analysis of radon awareness and disclosure policy in Kentucky: Applying Kingdon's multiple streams framework. *Policy, Politics, & Nursing Practice.*

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Research:
Unfunded Research Activities

Radon Reduction: Taking Action for a Healthy Home in the Primary Care Setting-
Co-investigator 2015-present

The Effect of Oncology Nurse Navigators on Patient Satisfaction Scores –
Co-investigator 2016

Stacy R. Stanifer
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