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Social Determinants of Health, Environmental Exposures and Home Radon Testing

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Abstract

Home radon testing is a primary lung cancer prevention strategy, yet the majority of Americans have not tested their home. This descriptive, ecological study uses 54,683 observed radon values collected in Kentucky homes from 1996 to 2016 to examine the association of county-level social determinants of health and environmental exposures on home radon testing rates. Multivariate linear regression analysis indicates that as median home value, rurality, and radon risk potential increased, counties experienced an increase in annual home radon testing rates. As adult smoking prevalence increased, counties experienced a decrease in annual rates of residential radon testing. These findings indicate that counties with low median home values, high adult smoking prevalence, and high incidence of lung cancer may benefit most from prevention interventions aimed at promoting home radon testing, adopting radon- and smoke-free home policies, and integrating radon risk reduction messaging into tobacco cessation and lung cancer screening programs.

Keywords

radon; social determinants of health; environmental exposure; lung neoplasm; risk reduction behavior

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 first classified as a carcinogen in 1988. Since that time, case-control studies examining the relationship between residential radon exposure and lung cancer in the general population have confirmed residential radon exposure as a risk factor for lung cancer (Darby et al., 2005; Krewski et al., 2006; Lubin et al., 2004). Furthermore, evidence demonstrates synergism between smoking and radon, putting those exposed to smoking and radon at greater risk of developing lung cancer (Darby et al., 2005; Krewski et al., 2006; Lubin et al., 2004; National Research Council Committee on Health Risks of Exposure to Radon [NRC], 1999).

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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 United States, 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 encourage 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; United States Department of Health and Human Services [USDHHS], 2005). Home radon testing can be accomplished with the use of do-it-yourself home radon test kits or by hiring a certified radon measurement professional (EPA, 2016).

Testing one's home for radon is a primary lung cancer prevention strategy and it 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). Social and economic disparities associated with home radon testing include lower income (Halpern & Warner, 1994; Hill et al., 2006; Nissen et al., 2012; Zahnd et al., 2018); lower education (Butler et al., 2018; Halpern & Warner, 1994; Nissen et al., 2012; Zahnd et al., 2018); lack of home ownership (Hill et al., 2006; Wang et al., 2000); and rurality (Zahnd et al., 2018). It is widely believed that disparities such as these are responsible for the health inequities facing many people around the globe. The U.S. Department for Health and Human Services *Healthy People 2020* emphasizes the importance of addressing social and physical determinants of health in order to improve the health of individuals and communities (USDHHS, 2014). In 2018, the World Health Organization (WHO) released the *WHO Housing and Health Guidelines* which offer evidence-based recommendations for creating healthy housing conditions as a way to reduce health inequities. The guidelines address numerous aspects of the home environment including exposure to radon (World Health Organization, 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).

Purpose

Kentucky, a state located in the Southeast portion of the United States, leads the nation in incidence and mortality from lung cancer (American Cancer Society, 2021). Much of the state's lung cancer incidence is likely due to the high prevalence of smoking and tobacco smoke exposure (Kentucky Department for Public Health and the Centers for Disease Control and Prevention, 2018); however, exposure to radon is likely a contributing factor as 93% of Kentucky counties have moderate-to-high radon exposure risk potential (EPA, 2003). Despite the increased radon exposure risk potential in Kentucky, fewer than 1% of homes are tested for radon each year (Radon Policy Division, n.d.). As a primary prevention strategy for lung cancer, identification of population-level factors associated with home radon testing is a public health priority and would help guide public health practitioners 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) on county-level rates of home radon testing. As living in a high-risk radon area has been known to prompt completion of home radon testing (Wang et al., 2000; Zahnd et al., 2018), we 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 the model to evaluate their potential to predict home radon testing. We 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. Additionally, we hypothesized that adult smoking prevalence would be associated with home radon testing based on findings from a recent individual-level study by our group 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 (Butler et al., 2018).

Method

Design & Sample

This was an ecological, descriptive study design using secondary data analysis of observed radon values from Kentucky homes collected from 1995 to 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, n.d.). Each recorded residential radon test was aggregated by the county and year in which the measurement was obtained. The number of tests per county per year was divided by number of households in the county and this ratio was multiplied by 10,000. This yielded an annual testing rate per 10,000 households for each county. These annual county-level rates were averaged across the 21 years to create an overall estimate of that county's rate of testing per 10,000 households.

Measures

Nine population-level predictor variables were assessed in this study. Six county-level social determinants of health variables included median household income, median home value, percent living below the 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. Three county-level environmental exposure variables included the upper quartile of the distribution of radon values, adult smoking prevalence, and lung cancer incidence rate. 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; Halpern & Warner, 1994; Hill et al., 2006; Nissen et al., 2012; Wang et al., 2000; Zahnd et al., 2018).

Social determinants of health variables.—Five-year estimates from the U.S. Census Bureau's 2006–2010 American Community Survey were used to measure county-level social determinants of health variables including median household income, median home value, percent living below the poverty level, percent of the population 25 years of age and older with a high school diploma or higher, and percent owner-occupied housing. As many counties in Kentucky are rural, American Community Survey data collected over a 5-year period from 2006 to 2010 were used in this study to provide a more precise multiyear estimate. The 2006–2010 date range was chosen as it falls approximately midway between the 1995 and 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 (codes range 1–9, 1 indicating the most urban and population-dense, and 9 indicating the most rural and least population-dense) (United States Department of Agriculture [USDA], 2019a).

Environmental exposure variables.—To determine a value for county-level radon exposure risk potential, we used the 54,683 observed residential radon values collected between 1995 and 2016 and obtained from the state database (Radon Policy Division, n.d.). 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 percentile, 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). This method of quantifying elevated exposure risk has been used in prior research (Kioumourtzoglou et al., 2019; Kjos & SchaeferGraf, 2007; Ohlander et al., 2013).

Adult smoking prevalence by county was measured using the Kentucky Behavioral Risk Factor Surveillance Survey (BRFSS) Annual Data Reports. Because the annual number of Kentucky 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 three-year average using data from the 2008, 2009, and 2010 Kentucky BRFSS reports. The years 2008–2010 were chosen as they corresponded closely with the American Community Survey data.

To calculate the lung cancer incidence rate in each county, new lung cancer cases were obtained from the Kentucky Cancer Registry for 1995 through 2016 (the most complete data available). A total of 93,616 lung cancer cases in Kentucky were obtained from the Kentucky Cancer Registry 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 were used to determine weighted average annual incident lung cancer rates per 100,000 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).

Statistical Analysis

Descriptive statistics using means, standard deviations, and ranges were used to summarize study variables. Multivariate linear regression was used to assess the association between county-level social determinants of health and environmental exposure variables on rates of residential radon testing in Kentucky. Variance inflation factors (VIFs) 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. This study was approved by the Institutional Review Board of a large public university located in the Southeastern United States.

Results

The average county-level aggregate annual residential testing rate was 13.4 per 10,000 households ($SD = 14.2$) ranging from 2.0 to 98.0 per 10,000 households. County-level social determinants of health and environmental exposures are summarized in Table 1. 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 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 multivariate linear regression to assess predictors of county-level residential radon testing rates was significant $F(7, 112) = 7.338$, $p < .001$ (Table 2). County-level median home value, percent living below the 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 31.4% of the variance in home radon testing rates. As shown in Table 2, median home value, RUC code, and upper quartile of the distribution of radon values 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 0.2 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 2.1. For each additional 1 pCi/L of radon exposure risk potential at the county level, annual rates of residential radon testing increased by 1.3 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 0.6.

Discussion

This study sought to examine the association between county-level measures of social determinants of health and environmental exposures on rates of home radon testing. Median home value, RUC code, radon risk potential, and adult smoking prevalence each made a unique significant contribution to the prediction of rates of home radon testing. As median home value, rurality, and radon risk potential increased, counties experienced an increase in annual home radon testing rates. As adult smoking prevalence increased, counties experienced a decrease in annual rates of residential radon testing.

To date, only one other study reported population-level disparities in home radon testing. Zahnd et al. (2018) utilized a zip code level of analysis to assess 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 as predictors of home radon testing in Illinois. Similar to Zahnd et al. (2018) our findings indicated that higher median home value was associated with greater rates of home radon testing. However, in contrast to Zahnd et al. (2018), the percentage of homes that were owner-occupied did not significantly contribute to the model. While neither Illinois nor Kentucky mandates home radon testing during the sale of a home, the variation in findings may be due to the differing policies in the two states that are intended to raise radon awareness among buyers and sellers during a real estate transaction (Stanifer & Hahn, 2020). As quality of housing has implications for people's health, these findings demonstrate the potential inequities in home air quality between those with greater affluence and those without. Because counties of lower affluence carry a greater burden of cancer mortality (Ward et al., 2004), radon risk reduction messages, programs and policies aimed at reaching lowincome populations are critically needed. Public health practitioners working with low-income families can educate them on the dangers of radon exposure and assist families in developing a plan to use low-cost strategies to reduce radon risk within their home (Larsson, 2014).

In contrast to our hypothesis and the study by Zahnd et al. (2018), we found rates of home radon testing were higher in rural areas. The level of analysis used by Zahnd et al. (2018) was zip code and the investigators utilized Rural–Urban Commuting Area Codes from the U.S. Department of Agriculture to determine zip code-level rurality (codes range 1–10, with 1 indicating the most urban and population dense and 10 indicating the most rural and least population dense) (USDA, 2019b). In Zahnd et al. (2018), investigators designated zip codes as either rural or urban by dichotomizing Rural–Urban Commuting Area Codes 1 to 3 as urban, and codes 4 to 10 as rural. In contrast, in the study reported here, we considered the full range of RUC codes from 1 to 9 to measure the gradient of urbanicity to rurality in each Kentucky County. 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, since even a small deviation in the number of tests in a county with a low population may have an outsize effect on the rate. Regardless, the mean annual home radon testing rate for Kentucky was low at 13.4 per 10,000 households and demonstrates the need for promotion of home radon testing in both rural and urban areas. One way to achieve this would be through the enactment of radon awareness and disclosure policies during real estate transactions. To that end, in December 2019, the Kentucky Real Estate Commission revised the *Seller's Disclosure of Property Condition* form to include a radon warning statement (Kentucky Real Estate Commission, 2019; Stanifer & Hahn, 2020). The warning statement is intended to educate the buyer about the dangers associated with radon exposure and raise awareness to the possibility that radon may be present in the home.

In our study, the upper quartile of the distribution of county-level residential radon values was significantly associated with annual residential radon testing rate. As county-level radon risk potential increased, so did residential radon testing rates. This finding is similar to other research in which investigators found more home radon testing occurring in areas the

EPA had classified as having risk for average indoor radon concentrations at or above 4.0 pCi/L, as opposed to areas of lower risk (Wang et al., 2000; Zahnd et al., 2018). While not explored in this 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. Previous research has shown that homeowners who knew others who had tested their home for radon were seven times more likely to plan to test their own home (Rinker et al., 2014). 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 formations (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 and lung cancer incidence as population level predictors of home radon testing. Contrary to our hypothesis (Butler et al., 2018), we discovered adult smoking prevalence was negatively associated with home radon testing rate. The lack of home radon testing among high smoking prevalence populations is particularly concerning given the synergism between smoking and radon on the development of lung cancer. Those who smoke tobacco and are exposed to radon have a 10-fold greater risk of developing lung cancer than nonsmokers (EPA, 2019); and evidence suggests that never-smokers exposed to secondhand smoke and radon may be at an increased risk for developing the disease (Lagarde et al., 2001). As a means of raising radon awareness, the WHO recommends that radon risk messaging be integrated into tobacco control programs (WHO, 2018). However, public health systems in the United States do not often integrate radon and tobacco control programs (Hahn et al., 2020). Adults who report smoking in the home would benefit from counseling on how to create a smoke- and radon-free home. 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 as those living without smokers to test for radon (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 also demonstrated that ready access to low-cost (Nissen et al., 2012) and free (Butler et al., 2018; Stanifer et al., 2020) 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 (Butler et al., 2018; Nissen et al., 2012; Stanifer et al., 2020) and places where tobacco cessation counseling occurs may serve as a cue to action and be one method to increase home radon testing among smokers and those exposed to secondhand smoke in the home.

In contrast to our hypothesis, higher county-level rates of lung cancer incidence were not significantly associated with higher county-level rates of home radon testing. As radon exposure is the second leading cause of lung cancer (American Cancer Society, 2021), this finding is concerning and has implications for health care providers. Physician recommendation has been shown to increase home radon testing (Nissen et al., 2012).

Therefore, delivering radon education to health care providers in counties with high lung cancer incidence may influence provider recommendations leading to an increase in home radon testing. Additionally, all health care providers can take advantage of teachable moments by including radon risk messaging during tobacco cessation counseling and when counseling smokers and former smokers on the risks and benefits of lung cancer screening.

Limitations are inherent in the use of population-level data. As Kentucky is comprised of 120 counties and the majority of them are rural with modest population sizes, annual rates of home radon testing and lung cancer incidence cannot be reliably calculated using single-year data estimates due to limited occurrences of both events. The 21-year time period was used to calculate stable rates of testing and lung cancer incidence, even in small counties. Future studies in more populous areas would benefit from the ability to consider the effect of time on these relationships. Additionally, Kentucky BRFSS and Census data are self-report and the former is a telephone survey; responses may have been influenced by this format, and those without phones were not eligible to be included. In addition, as population-level data were used, individual-level conclusions cannot be drawn. Finally, although we used every available test from the 21-year period, we acknowledge that not all radon tests conducted in the state were included in our data frame.

Despite the limitations, this study advances radon risk reduction research and has public health implications. In Wang et al. (2000) and Zahnd et al. (2018), 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 shown to vary considerably within each county (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 a more accurate measure of the true county-level radon risk potential and is a strength in this study. Additionally, the use of interval level measure of rurality of place (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. (2018), we would have lost the variability in urbanicity/rurality as there are multiple Kentucky counties within each of the 9 RUC categories, suggesting a binary variable for rurality is an oversimplification.

The prevalence of home radon testing remains low. Assessing county-level measures of social determinants of health and environmental exposures provides insight into population-level predictors of home radon testing rates. By identifying county-level predictors of home radon testing rates, interventions can be designed to address social determinants of health and reduce the disparities in home radon testing. Counties with low median home values, high adult smoking prevalence, and high incidence of lung cancer may benefit the most from prevention interventions aimed at promoting home radon testing, adopting radon- and smoke-free home policies, and integrating radon risk reduction messaging into tobacco cessation and lung cancer screening programs.

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Table 1.

Kentucky 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)	100.9 ± 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 100,000 aged ≥ 50 years)	289 ± 51.8	[184.0–432.0]

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 2.

County-Level Predictors of Home Radon Testing Rates in Kentucky ($N = 120$).

Regressor	Estimated *b (SE)*	Standardized Estimated *b*	*P* Value
County median home value (thousands of dollars)	.163 (.058)	.367	.006*
% living below poverty level	−.352 (.267)	−.161	.191
% owner-occupied housing	−.031 (.212)	−.013	.882
Rural–Urban Continuum Code	2.106 (.613)	.410	.001*
Upper quartile of radon (pCi/L)	1.323 (.347)	.319	.000*
Adult smoking prevalence, average yearly aggregate (%)	−.588 (.231)	−.237	.012*
Lung cancer incidence rate	.017 (.029)	.062	.555

Note. Rural–Urban Continuum Code 2003; adult smoking prevalence, 2008–2010; lung cancer incidence 1995–2016; All other variables 2006–2010.

* $p < .05$ indicates significance.