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Radon potential, geologic formations, and lung cancer risk

Ellen J. Hahn [a,*], Yevgeniya Gokun [a], William M. Andrews Jr. [b], Bethany L. Overfield [b], Heather Robertson [a], Amanda Wiggins [a], Mary Kay Rayens [a]

[a] Clean Indoor Air Partnership, College of Nursing, University of Kentucky, United States
[b] Kentucky Geological Survey, University of Kentucky, United States

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ABSTRACT

Objective. Exposure to radon is associated with approximately 10% of U.S. lung cancer cases. Geologic rock units have varying concentrations of uranium, producing fluctuating amounts of radon. This exploratory study examined the spatial and statistical associations between radon values and geological formations to illustrate potential population-level lung cancer risk from radon exposure.

Method. This was a secondary data analysis of observed radon values collected in 1987 from homes ($N = 309$) in Kentucky and geologic rock formation data from the Kentucky Geological Survey. Radon value locations were plotted on digital geologic maps using ArcGIS and linked to specific geologic map units. Each map unit represented a package of different types of rock (e.g., limestone and/or shale). Log-transformed radon values and geologic formation categories were compared using one-way analysis of variance.

Results. Observed radon levels varied significantly by geologic formation category. Of the 14 geologic formation categories in north central Kentucky, four were associated with median radon levels, ranging from 8.10 to 2.75 pCi/L.

Conclusion. Radon potential maps that account for geologic factors and observed radon values may be superior to using observed radon values only. Knowing radon-prone areas could help target population-based lung cancer prevention interventions given the inequities that exist related to radon.

Introduction

Lung cancer is the second most commonly diagnosed cancer and has the highest mortality rate of all cancers (National Cancer Institute, 2007). After smoking, radon is the second leading cause of lung cancer (Al-Zoughool and Krewski, 2009; U.S. Department of Health and Services, 2005). It is estimated that 15% of lung cancer cases in men and 53% in women are not caused by firsthand smoking (Sun et al., 2007). Based on residential case control studies in the U.S. and North America (Field, 2001; Field et al., 2006; Krewski et al., 2005), exposure to radon is associated with 15,400 to 21,800 cases, or approximately 10% of lung cancer cases in the U.S. annually (Committee on Health Risks of Exposure to Radon (BEIR VI), N.R.C. (1999)). It is important to note that most of the radon-induced lung cancers are among those also exposed to tobacco smoke (Lantz et al., 2013).

Radon is a colorless, tasteless, odorless radioactive gas derived from the decomposition of uranium in the soil and rock and it is found in every region in the U.S. Different geologic rock units have varying concentrations of uranium, producing fluctuating amounts of radon. Residential radon concentrations vary widely by geographic area (Hystad et al., 2014). Radon risk estimated from geology has been associated with lung cancer cases. In one Canadian case control study, the odds of lung cancer increased by 11% for every 10 years living in areas with geologic formations known to be associated with radon (Hystad et al., 2014).

Radon is typically summarized annually using geographical mapping of radon test values. These values are usually obtained from homeowners who request test kits from state and/or local health departments, and voluntarily test their homes. The data are then analyzed by commercial radon analysis laboratories and made available to state radon programs. In the U.S., political boundaries (i.e., county and zip code) are typically used to summarize the data. However, combining geological and radon survey data may be a better way to map radon potential (Miles and Appleton, 2005; Smethurst et al., 2008; Zhukovsky et al., 2012). Further, with limited resources, having a more accurate way to identify radon prone areas could inform population-based lung

* Corresponding author at: University of Kentucky College of Nursing, 751 Rose St.Lexington, KY 40536-0232, United States.
E-mail address: ejhahn00@email.uky.edu (E.J. Hahn).

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cancer risk reduction efforts and guide radon policy change (Garcia-Talavera et al., 2013). To date, few studies have considered geological rock formation type in the mapping of radon production potential (Smethurst et al., 2008).

This exploratory study measured environmental risk using geologic units and existing residential radon values to describe the radon production potential in Kentucky. Results are illustrated using geologic map boundaries rather than county borderlines. The objectives were to: (a) examine the spatial and statistical associations between observed radon values and geological formations from which radon is produced; and (b) create a better way to assess potential population-level lung cancer risk from radon exposure using geologic mapping.

Materials and methods

Design and sample

This is a secondary data analysis of observed radon values from Kentucky homes ($N = 309$) and geologic map unit data from the Kentucky Geological Survey. On generalized nationwide maps, most of Kentucky is located in high to moderate radon potential zones (U.S. Environmental Protection Agency, 1993) due to karst, a type of landscape that is formed by the dissolution of soluble rocks. Statewide residential radon data ($N = 938$) from 1987 were obtained from the Kentucky Geological Survey. These data were readily available; acquiring more recent data was beyond the scope of this project. The observed radon values were recorded in picoCuries per Liter (pCi/L), the typical unit of measurement in the U.S. (Field et al., 2006). A geographic subset of 309 radon values in north central Kentucky, an area with high radon concentrations, was used for this study. The remaining data points were not included because they were geographically dispersed, located in more sparsely populated rural areas; results would likely have been unreliable given very few radon values per geological formation category.

Geologic mapping

Radon value locations, reported as geographic coordinates, were plotted on existing digital geologic maps using ArcGIS and associated with specific geologic units. Geologic maps are a cartographic representation of geologic materials present at the earth's surface. Each map unit on a geologic map represents a package of different types of rock (limestone, shale, sandstone, etc.). Complete detailed geologic mapping is available in published and digital GIS formats for the entire state of Kentucky (Kentucky Geologic Map Information Service, 2014). In north central Kentucky, the area of interest with the greatest concentration of data points, the original digital geologic map data set included 35 separate named map units that had radon measurements. Using all 35 would have resulted in an unnecessarily large number of statistical categories and comparisons. For ease of analysis and interpretation, the 35 map units were grouped into 14 categories based on similarities in both rock type and age. This grouping was done by sequentially merging the map units that were the most geologically similar to each other. Not all geologic map units in the study area had identified radon measurements associated with them and they were not included in the study. One benefit of decreasing the number of categories from 35 to 14 rock formation groups was that each of the groups had at least five radon measurements. We investigated both a 14-group and a 7-group solution, but the former was superior in creating a division that was comprised of units that were relatively homogenous within the unit and heterogeneous among them.

Data analysis

Descriptive analysis was used to summarize radon values by geologic formation categories, including medians and ranges. Because the distribution of radon levels was right skewed, the Kruskal–Wallis test, a nonparametric alternative to one-way analysis of variance, was used to compare radon values among the 14 geologic formation categories. Post-hoc pairwise comparisons of radon levels among the formations were based on the Mann–Whitney U procedure with a Bonferroni correction to adjust for multiple comparisons. An alpha level of .0005 was used for this post-hoc test, given the 91 pairwise comparisons among 14 formation categories. To summarize the radon potential categories used to draw the map in Fig. 2, natural log transformation was used to decrease the degree of skewness in the radon values, and geometric means were used to describe each area. This type of transformation has been used previously with radon measurements (Beaubien et al., 2003), since they are typically right-skewed. A small constant value (0.25) was added to the two radon measures equal to zero so that the transformed version would be defined for all observations; this value was chosen as it was one-half the smallest non-zero value obtained. Although the log-transformed values could have been used both to develop the map as well as make quantitative comparisons among the formation categories, we used nonparametric tests for formation comparisons. Given the small sample sizes in some formation categories, this was a more conservative analysis strategy. All analyses were performed using SAS version 9.3 (SAS Institute, 2012).

Results

Description of geologic formation categories

Rock types identified in the study area were sedimentary and mainly included limestone, shale, siltstone, or dolostone. Each of these rock types have specific variations of mineral content, including trace amounts of radioactive materials that generate radon. Fig. 1 summarizes the identified map-unit categories and lists the subsequent dominant rock type and age associated with the geologic map unit. The 14 rock formation categories are labeled A through N.

Rock formation categories A through D are relatively young unconsolidated materials (Quaternary; less than 2.5 million years old) deposited in and near river valleys. These categories were separated based on the variation in their dominant sediment grain size (e.g., clay, silt, sand, gravel). Units E through N are all older bedrock units (Devonian, Silurian, or Ordovician; 350 to 440 million years old) that contain varying amounts of limestone, dolostone, shale, and siltstone.

Radon values and geologic formation categories

The Kruskal–Wallis chi-square test was significant ($\chi_{13,\,295} = 105.4$, $p < .0001$), indicating the radon levels varied significantly by geologic formation category. Post-hoc comparisons based on Mann–Whitney U tests are summarized in the last column of Table 1; formation categories with the same lowercase letter were not significantly different. There were three broad groupings of formation categories as show in the Table 1 and ordered by radon level: K, F, N, and L, with the highest levels, had median radon values ranging from a high of 8.10 to a low of 2.75 pCi/L; M, C, I, and E had median radon values ranging from 2.30 to 1.80; and G, H, J, D, A and B had median radon values ranging from 1.10 to 0.60. These groupings were distinguished by having similar medians within grouping and the two extreme groupings tended to have medians that differed from each other.

While Formation K only differed from Formation G in the pairwise comparisons, this was likely due the small number of observations in K. Formation F, with a lower median radon level than K but a larger number of observations, exhibited significantly higher radon values than Formations G through B. At the bottom of the Table 1, Formations G through B were typically not significantly different from each other, but they were significantly lower than most of the formations in the top group (K through L). The middle group of formations, M through E, had the distinguishing feature of not being significantly different

Age: System	Age: Series	Geologic unit		Dominant Rock Types	Test result category
Quaternary	Holocene	Alluvium		Silt, sand, clay, gravel	(A)
Quaternary	Pleistocene	Wisconsin glacial deposits		Sand, silt, gravel, clay	(B)
Quaternary	Pleistocene	Lacustrine deposits		Silt and clay	(C)
Quaternary	Pleistocene	Loess		Silt	(D)
Devonian	Middle	Sellersburg and Jeffersonville Limestones		Limestone	(E)
Silurian	Upper	Louisville Limestone		Dolomite and limestone	(F)
Ordovician	Upper	Drakes Formation (Rowland Member)		Dolomite, shale, limestone	(H)
Ordovician	Upper	Bull Fork Formation		Limestone and shale	(G)
Ordovician	Upper	Grant Lake Limestone		Limestone and minor shale	(H)
Ordovician	Upper	Fairview Formation		Limestone and shale	(I)
Ordovician	Upper	Kope Formation and Clays Ferry Formation		Shale and limestone	(J)
Ordovician	Upper	Lexington Limestone	Millersburg Member	Limestone and shale	(K)
Ordovician	Upper	Lexington Limestone	Strodes Creek Member	Limestone	(L)
Ordovician	Upper	Lexington Limestone	Tanglewood Member	Limestone and minor shale	(L)
Ordovician	Upper	Lexington Limestone	Brannon Member	Limestone and shale	(M)
Ordovician	Upper	Lexington Limestone	Grier Member	Limestone and minor shale	(N)

Fig. 1. Generalized stratigraphic column showing geologic units beneath all areas where radon measurements were taken in Kentucky, with stratigraphic order ranging from youngest (top—Quaternary) to oldest (bottom—Ordovician); geologic units from which no radon measurements were obtained were omitted from Fig. 1. Some units were grouped together based on similar geology or stratigraphic position.

from either the formations in the top group (K–L) or the formations in the bottom group (G–B).

Mapping of radon values and geologic formations

Geometric means for each of the 14 rock formation categories were determined using the log-transformed radon values and were mapped to show radon level trends in the study area. Fig. 2 shows a preliminary map of geologic potential for the production of radon in north central Kentucky. Black dots show the location of the 309 radon measurements used for this analysis. Geologic unit categories are shown with gray-scale shading corresponding to their associated average radon value. County boundaries are shown for geographic reference, and to illustrate the variety of geologic radon potential within a county. Areas underlain by geologic units with no radon measurements are shown in white on the map. The locations of the radon measurements were clustered in the larger population centers of the state. The units with the highest average radon measurements were located in central Kentucky. Geologic formation units varied greatly across and within county boundaries.

Table 1
Descriptive summary of 1987 radon values in Kentucky by geologic rock formation category, with analysis of variance post-hoc comparisons ($N = 309$).

Formation category	Sample size (n)	Median	Range	Post-hoc comparisons[a]
K	5	8.10	5.20–11.90	a b c d f g h i j
F	40	5.40	0.70–25.00	a b c d
N	41	3.50	0.50–31.20	a b c d f
L	28	2.75	0.00–20.20	a b c d f g i
M	15	2.30	0.50–14.80	*
C	9	2.20	0.90–6.80	*
I	9	1.90	0.70–11.70	*
E	23	1.80	0.50–22.30	*
G	45	1.10	0.50–7.30	e f g h i j
H	13	1.00	0.50–6.60	a c d e f g h i j
J	14	0.90	0.50–13.70	a d e f g h i j
D	36	0.85	0.00–10.40	a e f g h i j
A	20	0.70	0.50–8.20	a d e f g h i j
B	11	0.60	0.50–2.70	a e f g h i j

"*" These medians did not differ significantly from any other group.
[a] Medians with the same lower case letter are not significantly different from each other at $\alpha = .0005$.

Discussion

Observed radon levels varied significantly by geologic formation category. Of the 14 geologic formation categories in north central Kentucky, four were associated with high average radon levels, ranging from a high of 8.10 (median value) to a low of 2.75 (median) pCi/L. Two of these four formation categories had median radon values of 4.0 pCi/L or greater, the EPA action level for radon (U.S. Environmental Protection Agency (EPA), 2012). The two geologic formation types with the highest radon levels were older bedrock units (Ordovician or Silurian; 350 to 440 million years old). The geologic formation categories with the highest median radon levels were: Millersburg Member (limestone & shale) and Louisville Limestone (dolomite & limestone). Similarly, the two other geologic formation types that were associated with the highest radon levels were Grier Limestone (limestone & minor shale) and Tanglewood Limestone Member (limestone & minor shale). The geologic formation categories with the highest average radon measurements were located in central Kentucky.

Maps that illustrate radon potential typically use political boundaries to summarize the data. As our findings demonstrate, geologic formation units varied greatly across and within county boundaries. Given that radon is geologically produced, county boundaries are likely not the best unit of analysis for considering radon potential. This exploratory study examined geology to better illustrate the geographic distribution of radon potential, and this method was found to be a valid and more accurate approach than using political boundaries.

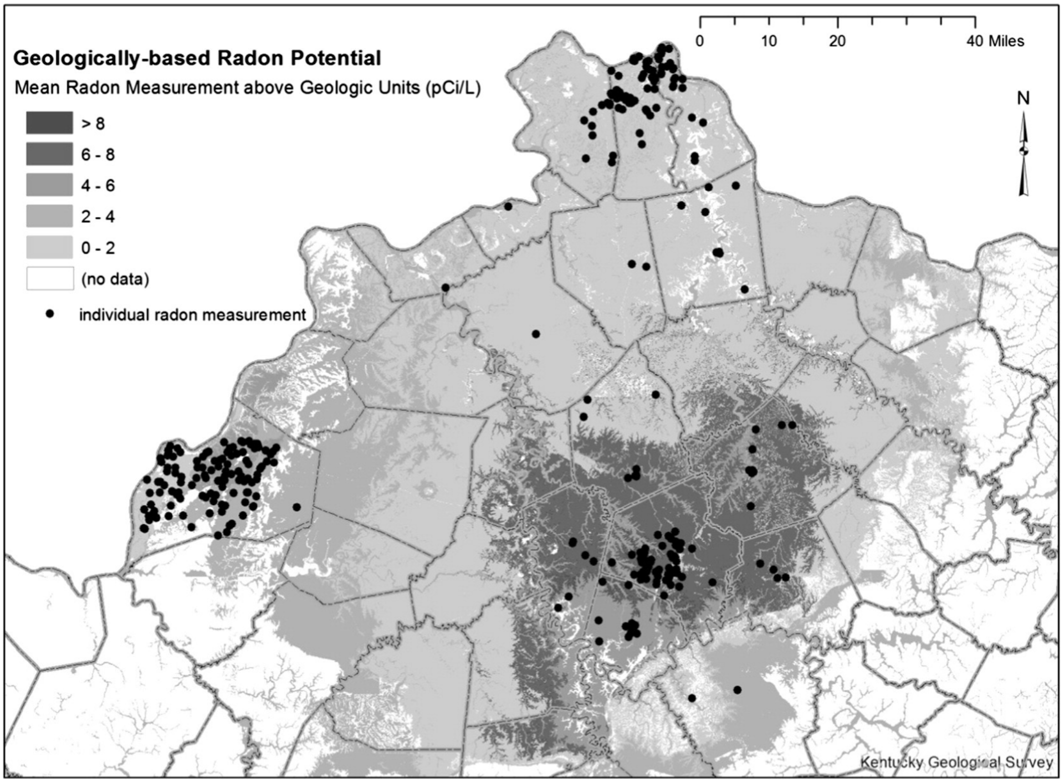

Fig. 2. Geologic potential for radon production in north central Kentucky.

Our findings are consistent with other studies showing that geological factors and indoor radon concentrations are associated; however there are other factors that must be accounted for such as soil structure, groundwater conditions, ventilation, and condition of the building (Sundal et al., 2004). Measures of these other important factors were beyond the scope of the study reported here. Regardless of these other factors, using a map that accounts for both geologic factors and observed radon values is a superior method compared to using observed radon values only. However, state radon programs typically update the radon maps by county and zip code based on the radon testing data the state receives. For example, the Kentucky Radon Program compiles observed radon values, county, and zip code from kits analyzed by three laboratories over time, and they partner with Western Kentucky University to regularly update the maps using all available data regardless of missing county-level data. Based on the findings reported here, this limited method of mapping is inadequate to accurately assess population-level risk from radon exposure. Use of an enhanced combined mapping approach has the potential not only to better inform the public of radon risk but also to accurately target specific radon-prone geographic areas with evidence-based risk reduction interventions (e.g., population-based contests to promote radon testing (Hahn et al., 2014a, 2014b) and home screening for both radon and secondhand smoke (Lantz et al., 2013) as an integral part of primary care (Hahn et al., 2014a, 2014b)). For example, knowing that homes are located on the geologic formation of Millersburg Member (limestone & shale), preventive health interventions to reduce radon exposure could be targeted to homeowners, especially current and former smokers (Lantz et al., 2013) living in these locations.

Reducing radon exposure in the general population relies on people testing their homes. However, the vast majority of homeowners do not test their homes for radon. One study found that 82% of respondents had heard of radon but only 15% had tested for radon (Wang et al., 2000). Although most respondents reported having heard of radon, 50% or fewer knew that radon was associated with lung cancer (Duckworth et al., 2002; Wang et al., 2000). Some do not test their homes for radon because they believe they are less at risk than those around them, regardless of their actual risk (Weinstein et al., 1991). People may choose not to test for radon because they believe that radon is not a serious problem in their home or geographic area (Rinker et al., 2014; Wang et al., 2000). On the other hand, if people know someone who has tested for radon, they are more likely to plan to test their home (Rinker et al., 2014).

Our findings have implications for policy change requiring builders to use Radon Resistant New Construction (RRNC), a set of construction techniques that can lower radon levels by as much as 50% (U.S. Environmental Protection Agency, 2008). Most states have no state or local laws requiring RRNC (U.S. Environmental Protection Agency, 2013). Only four states mandate RRNC, but local jurisdictions must adopt them (Florida, Maine, Rhode Island, and Virginia). Our findings may prompt policymakers to require builders to use RRNC especially in locations with high risk geologic formations. However, most of the nation is still in the early stages of awareness regarding the need for radon policy. Our findings are promising in that they provide a snapshot of the local landscape that can be used to target radon risk reduction interventions such as policy change requiring builders to use RRNC.

This study has several limitations. First, the data are limited to one region of Kentucky with high radon concentrations. Second, it would be difficult to apply the exact geologic groupings used in this study to other areas as these rock formation types are specific to the selected geographic location. These concerns are minimized by the fact that this method could be applied to other regions (assuming the targeted region has both a sufficient number of radon measurements and existing digital geologic maps), leading to a tailored set of geological groupings for the given region. Third, while all rock formation categories included at least five radon measurements, the number of radon values in the study is relatively small. Future studies with a greater number of radon values per formation category would allow the use of parametric methods for group comparisons. Finally, consideration of the role of housing type and construction practices were beyond the scope of this study, and warrant further investigation of the associations among housing factors, geologic formations, and radon level. Future research will benefit from a more widespread pattern of testing for radon, and mapping of both radon potential and tobacco smoke exposure (Lantz et al., 2013).

Conclusions

Lung cancer is the single most preventable form of cancer. Radon is the second leading cause of lung cancer, and there are wide geographic variations in radon exposure. Yet, most people do not test their homes for radon and many are unaware of the well-established link between radon and lung cancer. Research is critically needed to identify areas that are prone to both high radon concentrations and tobacco smoke exposure so that prevention interventions can be targeted to those most at risk (Lantz et al., 2013). Current maps that are based solely on political boundaries as they relate to observed radon values may not adequately illustrate estimated radon potential. Given the population health risks from radon exposure and the wide geographic variations of exposure, the findings of this exploratory study suggest that combining observed radon values and geologic information may provide better maps for identifying and targeting radon-prone areas with preventive interventions. Taking into consideration the inequities that exist related to radon levels, identifying radon-prone areas is the first step in developing and testing effective and practical population-based lung cancer prevention interventions.

Conflict of interest

The authors declare that there is no conflict of interest.

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