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The use of gamma-survey measurements to better understand radon potential in urban areas☆

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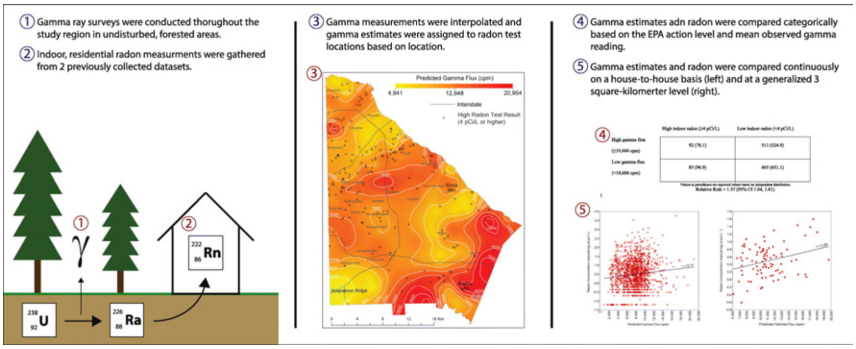
HIGHLIGHTS

- Efficacy of in situ gamma surveys in place of unavailable areal data to determine radon exposure potential is analyzed.
- In situ gamma readings show weak but positive relationships with indoor radon on a house by house basis.
- At courser spatial resolutions the positive association between gamma surveys and average indoor radon is stronger.
- In situ gamma surveys may function as a predictor of generalized radon potential when combined with other variables.

GRAPHICAL ABSTRACT



① Gamma ray surveys were conducted thorughout the study region in undisturbed, forested areas.

② Indoor, residential radon measurments were gathered from 2 previously collected datasets.

③ Gamma measurements were interpolated and gamma estimates were assigned to radon test locations based on location.

④ Gamma estimates adn radon were compared categorically based on the EPA action level and mean observed gamma reading.

⑤ Gamma estimates and radon were compared continuously on a house-to-house basis (left) and at a generalized 3 square-kilomerter level (right).

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ABSTRACT

Accounting for as much as 14% of all lung cancers worldwide, cumulative radon progeny exposure is the leading cause of lung cancer among never-smokers both internationally and in the United States. To understand the risk of radon progeny exposure, studies have mapped radon potential using aircraft-based measurements of gamma emissions. However, these efforts are hampered in urban areas where the built environment obstructs aerial data collection. To address part of this limitation, this study aimed to evaluate the effectiveness of using in situ gamma readings (taken with a scintillation probe attached to a ratemeter) to assess radon potential in an urban environment: DeKalb County, part of the Atlanta metropolitan area, Georgia, USA. After taking gamma measurements at 402 survey sites, empirical Bayesian kriging was used to create a continuous surface of predicted gamma readings for the county. We paired these predicted gamma readings with indoor radon concentration data from 1351 residential locations. Statistical tests showed the interpolated gamma values were significantly but weakly positively related with indoor radon concentrations, though this relationship is decreasingly informative at finer geographic scales. Geology, gamma readings, and indoor radon were interrelated, with granitic gneiss generally having the highest gamma readings and highest radon concentrations and ultramafic rock having the lowest of each. Our findings indicate the highest geogenic radon potential may exists in the relatively undeveloped southeastern part of the county. It is possible that in situ gamma, in concert with other variables, could offer an

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☆ The findings and conclusions in this study are those of the authors and do not necessarily represent the official position of the Centers for Disease Control and Prevention or the Agency for Toxic Substances and Disease Registry.

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alternative to aerial radioactivity measurements when determining radon potential, though future work will be needed to address this project's limitations.

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1. Introduction

Radon gas is one of the most common radioactive elements to which people are exposed (Kauppinen et al., 2000), with indoor air concentrations of radon typically ten times higher than average outdoor concentrations (Harley et al., 1988; UNSCEAR, 1994). As the radon decays the resulting radon products, called radon progeny, can be breathed in and lodged in lung tissue, delivering a dose of radiation when they decay further (Keith et al., 2012). Therefore, radon progeny account for as much as 37% of the average American's lifetime radiologic dose (Schauer, 2009). Increasing cumulative radon progeny exposure, either through increased duration or increased magnitude, is directly correlated with heightened lung cancer risk (National Research Council, 1999; WHO, 2009; Planchard and Besse, 2015; Kang et al., 2016). As a result, only smoking leads radon as a cause of lung cancer; radon is responsible for 3 to 14% of all lung cancer deaths worldwide, with most of these deaths occurring in smokers who are at increased risk of radon induced lung cancers (Darby et al., 2001; National Research Council, 1999; Gray et al., 2009; World Health Organization, 2009; Noh et al., 2016; Oh et al., 2016; Sheen et al., 2016). In the United States specifically, based on mid 1990's data (National Research Council, 1999), radon accounted for an estimated 21,100 deaths annually (EPA, 2003, 2009).

Radon emanates from materials containing the unstable radionuclides, thorium-232 (^{232}Th) and uranium-238 (^{238}U) (National Research Council, 1999; Peterson et al., 2007). The ^{238}U decay series specifically forms gaseous radon-222 (^{222}Rn) via the alpha decay of solid radium-226 (^{226}Ra) (Sakoda et al., 2011). This is important because ^{222}Rn is generally the most common radon isotope found in buildings, though buildings on thorium rich soil may have elevated concentrations of thoron (^{220}Rn) (WHO, 2009).

The decay of ^{238}U and its daughters in soil and bedrock forms radon. The amount of ^{238}U contained in an area's soil and underlying bedrock will directly impact the amount of geogenic ^{222}Rn released to the air in that area. However, the concentration of ^{238}U is not uniform across all geologies; for example, areas of granitic bedrock are expected to have relatively high ^{238}U (Quindós Poncela et al., 2004; Muikku et al., 2007). Increased permeability and porosity of bedrock and its overlying soil increases the rate of ^{222}Rn released into the surrounding groundwater and air (Bossew and Lettner, 2007). The presence of faults can also affect ^{222}Rn concentrations by providing pathways for radon to escape (Pereira et al., 2010).

Home-construction characteristics also affect indoor radon concentrations. Homes lacking structural defects may have low indoor radon concentrations even if the geogenic radon emissions are high (Vaupotic et al., 2002). If there are foundation cracks or unsealed concrete joints, then radon will likely flow into the often lower pressure of the home via the defect (Appleton, 2007). Additionally, climate controls within the home will alter temperature and humidity, which can affect indoor air pressure (e.g., air conditioning can create a pressure gradient that draws air into the home) and thus rates of ^{222}Rn infiltration (Akbari et al., 2013). Finally, building materials, especially concrete and wallboard, can contain ^{238}U and its decay products such as ^{226}Ra; therefore, as these decay, the building materials that contain them can become sources of ^{222}Rn (Chen et al., 2010).

1.1. Radon potential

In response to the national and international health hazard posed by radon, some have attempted to predict indoor radon concentrations using geology. The process involves generalizing known radon concentrations, which are sparsely sampled, to the underlying geology, which is spatially continuous, and using the radon-geology relationship to extrapolate radon values across a region (Cinelli et al., 2011). However, the lack of indoor radon concentration data in homes and the at times inaccuracy of geologic data are major limitations of radon-geology studies (Chen, 2009; Friedmann and Groller, 2010). Often these studies only find correlations between some rocks (e.g., granite, shales, and U-enriched phosphate rocks) and radon concentrations (Buttafuoco et al., 2007), leaving the understanding of the relationship between other rock types and radon unexplained. In some cases, only a quarter of all variation in radon concentration can be explained by geology (Appleton and Miles, 2010). Further, this method necessitates that both indoor radon concentration and geologic data be available and reliable.

Using gamma radiation instead of, or in addition to, geology should improve radon potential mapping. Gamma radiation is produced naturally as a result of the decay of some radioactive elements, including potassium-40, uranium-235, ^{232}Th, ^{238}U, and others (Wilford, 2012). ^{238}U, which as noted earlier is the progenitor of ^{222}Rn, is so well linked to gamma radiation that gamma spectroscopy was used for uranium mining exploration (Wilford and Minty, 2007). It is worth noting that overall gamma emissions in an area are the result of the combined radioactive decay of a variety of radionuclides. Gamma emissions also have been shown in certain circumstances to have a direct relationship to soil ^{226}Ra (García-Talavera et al., 2013), which is in turn correlated to indoor ^{222}Rn (Nason and Cohen, 1980; Jackson, 1992; Szegvary et al., 2007a). One study found that equivalent ^{238}U concentrations, derived from aerial gamma emission rate measurements, was the most important independent variable in predicting radon potential (Appleton et al., 2011a). Other studies report that gamma dose rate accounts for as much as 60% of radon flux variability (Szegvary et al., 2007b; Griffiths et al., 2010). Still more studies have found that the inclusion of gamma emission rates with other variables, such as bedrock and surficial geology can lead to greatly improved radon potential maps (Smethurst et al., 2008; Ielsch et al., 2010).

Despite the potential of using gamma emissions for radon mapping, the use of aerial gamma measurements has serious limitations. These measurements have relatively large spatial resolutions (e.g., 1 km plus) (Appleton et al., 2011b; Drolet et al., 2013) resulting in the inclusion of the built environment features in the sample pixels, which can artificially increase or decrease gamma readings. Further, legal restrictions require aircraft to fly higher over cities than rural areas (14 C.F.R. § 91.119) introducing additional error because the accuracy of gamma measurements decrease exponentially with distance from the ground (Appleton et al., 2008). Gamma surveys in urban environments also run the risk of introducing confounders directly from building materials. Previous work has shown that indoor gamma dose rate can be higher than outdoor dose rate as a result of gamma emitters found in building materials (Clouvas et al., 2001). While building materials can clearly have a large impact on gamma dose rate, they are understood to play a minimal role in indoor radon concentrations in the majority of cases (EPA, 2009). Thus aerial gamma surveys that cannot distinguish between natural and built environments run the risk of measuring gamma flux from sources that do not play an important role in determining radon.

1.2. Purpose

Therefore, the purpose of this study is to evaluate the effectiveness of in situ gamma instrument readings from nearby/interspersed undisturbed environments for assessing radon potential in urbanized environments. The two main objectives are as follows: (1) to create a spatially complete