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Indoor Radon Levels and Lung Cancer Incidence on Guam

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Abstract

Radon (Rn) is a naturally occurring, radioactive gas that impacts air quality world-wide. It is a known carcinogen and considered by the United States Environmental Protection Agency (U.S. EPA) to be the second leading cause of lung cancer after tobacco smoking. Of several known isotopes of radon, ^{222}Rn is the most stable with a half-life of approximately four days. This particular isotope is associated with the uranium (^{238}U) decay series and accounts for most public ionizing radiation exposures. Most global indoor ^{222}Rn emanates from granitic bedrocks located underneath buildings. While such rocks are absent on Guam, the karst limestone formations that overlay the island's basement volcanics (basalt) are of biogenic origin and are believed to be a significant source of radon. In a recent multi-year survey conducted on Guam by the local EPA, indoor ^{222}Rn levels exceeded the U.S. EPA air quality standard of 4 pCi/L in ~40% of all buildings tested. Concentrations were log-normally distributed and exceeded 300 pCi/L in two instances. Weighted average indoor ^{222}Rn levels were generally much higher in villages from the northern half of the island where limestone coverage predominates. The relationship between ^{222}Rn and lung cancer incidence on Guam was examined in the study reported here. The results were strongly suggestive of a hormetic effect existing between the two variables. Possible confounding effects attributable to smoking and ethnicity were examined and found to be insignificant. In fact, ethnic groups predominantly confined to the northern half of the island (i.e., Filipinos and all other Asians as a collective group) showed considerably lower cancer incidence and mortality rates than the indigenous Chamorro people who are well represented island-wide. The findings of the study lend further weight to numerous other reports that suggest low-level exposures to ^{222}Rn have a beneficial health effect. They also support a growing critique of the rationale behind the U.S. EPA adopted linear-no-threshold toxicological model, which assumes that any dose of radiation is harmful, no matter how small. Finally, they also imply that the current U.S. EPA action level of 4 pCi/L for indoor radon is overly conservative and needlessly prompting homeowners to install radon mitigation systems into buildings that really don't need them.

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Keyword: radon; radon progeny; lung cancer; confounding effects; hormesis; risk assessment

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1. Introduction

Radon is a short-lived, naturally occurring, radioactive gas formed during the normal decay of uranium and thorium to stable lead [1]. Of 39 known radon isotopes, ^{222}Rn is the most stable with a half-life of 3.8 days[2]. This particular isotope is part of the uranium (^{238}U) decay series[3] and is generally the most commonly encountered indoor radon nuclide[4]. All radon isotopes decay by alpha particle emission into charged progeny. Unlike gaseous radon, these progeny exist in the solid phase[5] and tend to form small molecular clusters, or attach to aerosols or dust particles in the air[6]. Although ^{222}Rn and its progeny are easily inhaled and can penetrate deep into the airways of the lung, only alpha emissions from the short-lived polonium daughters (^{214}Po and ^{218}Po) are considered to be of sufficient energy to damage the DNA of sensitive respiratory tissues[7,8].

An association between radon and lung cancer was first recognized in underground miners in the early part of the twentieth century[9,10], but a causal relationship between the two variables was not generally accepted until the 1960s[1]. Concerns over indoor radon exposures and lung cancer emerged during the late 1980s after it was equivocally established that radon was a universal indoor-air contaminant[11]. At about the same time, radon was officially classified as a human carcinogen by the International Agency for Research on Cancer[12] and scientific interest in its health effects escalated. By the mid 1990s it was widely publicized that radon was the second leading cause of lung cancer after smoking[1]. Shortly thereafter, the U.S. Environmental Protection Agency (U.S. EPA) estimated that indoor radon exposures account for approximately 21,000 lung cancer deaths annually in the U.S.[13]. This represents about 14% of all U.S. lung cancer deaths[12].

Although it is not feasible to completely eliminate radon from indoor air, mitigation systems are available to homeowners and currently cost anywhere between $1,000 and $3000[14]. The U.S. EPA has established a national mitigation action level for indoor radon of 4 pCi/L. Under this advisory, homeowners are strongly encouraged to mitigate their homes for radon levels of 2 pCi/L and above[15]. Average outdoor radon concentrations in the U.S. apparently hover around 0.4 pCi/L[15] (range: 0.2-0.7 pCi/L)[16]. The tolerance window between normal background radon levels and the mitigation threshold is, therefore, fairly narrow. Given the existence of numerous locations in the world where outside air radon levels greatly exceed 4 pCi/L, and where residents show no obvious signs of ill health[17], the appropriateness of the U.S. EPA mitigation standard is frequently called into question[18].

Levels of ^{222}Rn inside buildings depend on a variety of factors, but ultimately reflect the uranium content of the underlying strata. Granitic bedrocks contain relatively high levels of this element (up to 20 mg/kg) and rank among the more common geological formations that contribute radon to indoor air[19]. Granite is not found on Guam where relatively high indoor ^{222}Rn levels occur in the northern half of the island[20,21]. In fact, all volcanic rocks on the island are composed of basalt and contain relatively low levels of uranium (0.4 mg/kg)[22,23]. In northern Guam, however, the basement volcanics are covered by a highly porous, karst limestone plateau to a depth exceeding 200 meters in places[20]. The limestone is of biogenic origin and is composed largely of fossilized foraminifera and corals[20]. Uranium in the hard tissue of living corals[24,25] are comparable with average values (4-5 mg/kg) found in granite[22,26]. Forams, on the other hand, generally contain much lower concentrations of this element (<0.1 mg/kg)[27], although much higher values (up to 10 mg/kg) have been reported in the manganese-rich diagenetic layer that forms on their carbonate remains in sediment layers[28].

Perhaps of greater importance here, though, is the fact that karstic limestone formations are highly fractured and provide a rapid means of radon transport into overlying soils and buildings[29]. Whatever the reason for the relatively high radon levels in northern Guam, the pronounced differences in radon activity between north and south, coupled with fairly stable village populations of mixed ethnicity, makes the island an ideal setting for examining the relationship between indoor radon and lung cancer in a community distanced from atmospheric pollution generated by the more industrialized nations of the world. Such was the principal focus of the investigation described herein.

2. Materials and Methods

The study makes use of information gathered independently by others with different research objectives than our own. This, of course, introduces unavoidable uncertainties into our analyses of possible relationships between the data-sets. Nevertheless, we feel our preliminary findings are of sufficient interest to report here. Hopefully the trends they uncover and the questions they raise will promote a more detailed investigation later on. Weaknesses in the data-sets, at least from our perspective, are described below.

Guam has 19 villages distributed in approximately equal proportions between the northern and southern halves of the island. Indoor ^{222}Rn levels were determined in each of these villages by the Guam Environmental Protection Agency (GEPA) from 2002 to 2009. A total of 2403 samples from 1871 buildings (schools, public buildings and homes) were analyzed. GEPA employed a passive sampling technique using 4-inch diameter, open-faced, metal canisters filled with ~75 g of activated charcoal. The charcoal served as a radon adsorption site and was exposed to ambient indoor air under closed room conditions for a nominal period of 48 hours[20]. Most residential samples were collected and delivered to the agency by homeowners who obtained canisters free of charge from GEPA following various outreach activities and media campaigns to promote greater radon awareness in the community. As a result of the well advertized statement that indoor radon exposures in northern Guam are generally high, plus the fact that 80% of the island population live there, most of the samples received (88%) were from buildings in this part of the island. ^{222}Rn analysis was subsequently performed by GEPA using sodium iodide crystal based detection equipment. Quality control and quality assurance protocols are briefly outlined elsewhere[21]. The data provided by GEPA contained records of the annual number of samples taken from each village; the annual average ^{222}Rn concentrations recorded for each village, and all individual ^{222}Rn determinations of 4 pCi/L and above. Values below the USEPA action level were not included. Weighted average indoor air ^{222}Rn concentrations were calculated for each village over the 8-year sampling period from the information provided.

Lung cancer incidence data for 1993-2007 were obtained from the Guam Division of Public Health and Social Services (DPHSS) and the Guam Cancer Registry. Six hundred and forty nine (649) lung cancer cases were recorded on Guam over this time frame. The data-sets provided were age-unadjusted (crude) statistics for males, females and dominant ethnic groups. Because of the relatively small number of lung cancer cases recorded for some villages, we pooled the data for all subgroups over the 15-year period to derive the total number of lung cancer within each village. These values were then normalized to a population size of 100,000 and finally expressed as annual lung cancer incidences per village. No details were given as to the age and smoking habits of each cancer victim, their address, or how long they had lived in their particular village.

In 2001-2003, smoking prevalence surveys were conducted on Guam by the Guam Behavioral Risk Factor Surveillance System (BRFSS) program under the auspices of DPHSS. Respondents in the survey were classified as either smokers or non smokers depending on whether or not they had smoked 100 cigarettes or more over their lifetime. No other information or data were provided. The number of people questioned in each village was relatively small and accounted for 0.1-2.9% the total village populations (average: 0.6%). The data were appropriately weighted to account for variations in age, gender and ethnicity distributions although no details were given. Annual smoking prevalences over that time frame varied within villages by factors ranging from 1.04-2.79. Because of this and the relatively small number of respondents, the data collected were once again pooled for our study to provide a single value for each village for the 3-year period over which the BRSFF surveys were conducted.

3. Results and Discussion

3.1. Indoor radon levels

The number of charcoal canisters analyzed for ^{222}Rn by GEPA over the 2002-2009 sampling period ranged from 17-492 (median: 152) and 1-96 (median: 23) for northern and southern Guam villages respectively. These values were loosely correlated with village population sizes (r=0.71), which, in 2000, ranged from 1,100-42,920 in the north of the island and from 887-7,500 in the south[30].

Individual indoor ^{222}Rn levels determined island-wide ranged from <4-352 pCi/L. Values were log-normally distributed with 63% below the U.S. EPA action level of 4 pCi/L (Fig. 1). ^{222}Rn concentrations were below the U.S. EPA action level in 60% and 80% of all northern and southern Guam samples respectively. Village weighted averages ranged from 2.4-17.3 pCi/L in the northern half of the island Guam and from 0.3-3.2 pCi/L in the south.

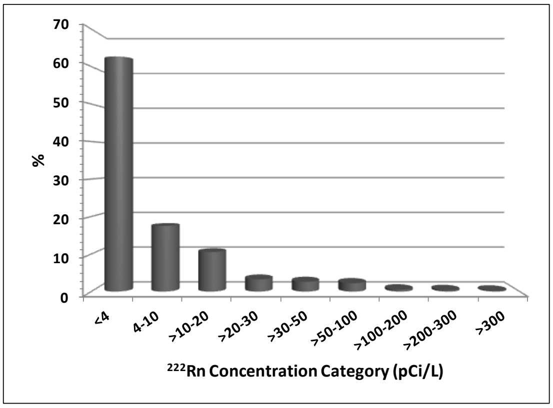

Fig. 1. Frequency distribution histogram of indoor ^{222}Rn levels recorded in Guam buildings by GEPA from 2002 to 2009.

Interestingly, the five northern villages with the highest weighted average ^{222}Rn concentrations: Dededo (17.3 pCi/L), Yigo (14.1 pCi/L), Barrigada (10.1 pCi/L), Mangilao (8.6 pCi/L) and Tamuning (7.6 pCi/L), is where 66% of Guam residents live. Dededo is the most densely populated village and home to almost 30% of the island population. Thus, approximately two thirds of Guam residents may be chronically exposed to indoor radon levels that exceed the U.S. EPA action level.

3.2. Lung cancer incidence

The number of lung cancer cases reported for each village between 1993 and 2007 ranged from 5-159 and were tightly correlated with village population size (r=0.95). In view of the generally higher indoor ^{222}Rn levels in northern Guam and the relatively large number of people living there, one might expect the incidence of lung cancer on the island to be higher in the north than the south. This does not appear to be the case, however. On the contrary, there is a highly significant negative relationship between the two variables that is difficult to explain based on data inadequacies alone (Fig. 2). Indeed, the data suggests that either residents in northern Guam are more resilient to lung cancer than their southern counterparts, or there is some hidden variable, or confounding factor, that is masking the true effect of ambient radon and its progeny on the incidence of lung cancer in the Guam population as a whole.

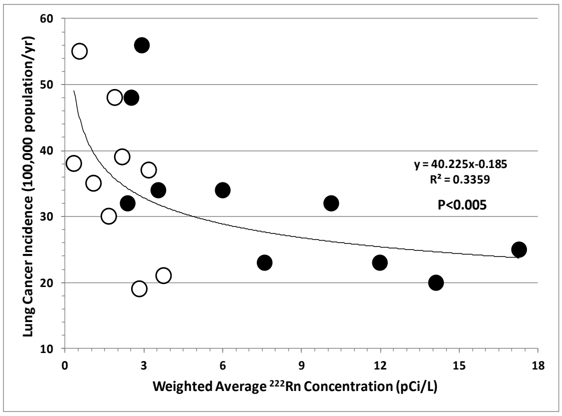

Fig. 2. Scatter plot of lung cancer incidence against indoor ^{222}Rn concentrations. Filled and open circles represent data-sets from northern and southern Guam villages respectively. Regression equation and R^2 value shown for line of best fit. ‘P’ represents significance level of linear correlation coefficient (r=0.580) derived from natural log transformed data-sets.

A confounding factor may be defined as an extraneous or hidden variable that correlates with both the dependant and independent variables masking their true relationship with one another[32,33]. The two most likely confounding candidates considered during the present study were smoking and ethnicity. These are discussed separately below.

3.3. Smoking

It is now well established that smoking is the leading cause of lung cancer in the USA and is directly responsible for ~90% of all lung cancer cases nation-wide[1]. A recent BRFSS report concluded that smoking prevalence on Guam (from surveys conducted annually from 2001-2003 and 2007-2010) exceeded the national average with one in three males and one in five females smoking on a daily basis[34]. The data we received from the earlier (2001-2003) BRFSS survey yielded average smoking prevalences in each village of 16-55% (median 29%). Median values for northern and southern villages considered separately were very similar at 29% and 31% respectively.

According to the BRFSS report, 40% of Chamorros smoke compared with only 12% of Filipinos. The Chamorros are the indigenous people of Guam and the dominant ethnic group island-wide with a total population of ~60,000[31]. They account for 16-16% (median: 47%) of village populations in the northern half of the island and 23-93% (median: 68%) in the south. In sharp contrast, 90% of Filipinos, who represent the second largest ethnic group on island (population: 41,000), reside in the north of the island. These facts alone suggest that smoking may very well be an important confounder in this study. However, our analysis of the earlier 2001-2003 BRFSS data-sets showed that although village smoking prevalences generally increased with increased Chamorro representation in village populations, the trend was not significant at the 95% confidence level. Additionally, a significant relationship between smoking prevalence and lung cancer incidence on island could not be demonstrated (Fig. 3). The likelihood of confounding by smoking therefore seems unlikely under the circumstance, despite a significant inverse relationship existing between village smoking prevalences and weighted average ^{222}Rn concentrations (Fig. 4).

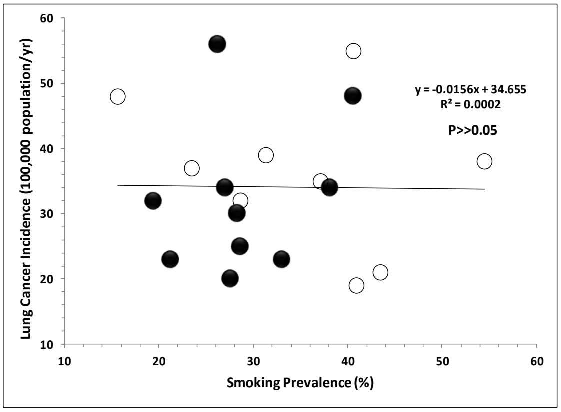

Fig. 3. Scatter plot of lung cancer incidence against smoking prevalence. Filled and open circles represent data-sets from northern and southern Guam villages respectively. Regression equation and R^2 value shown for line of best fit. 'P' represents significance level of linear correlation coefficient (r=0.014) derived from raw data-sets.

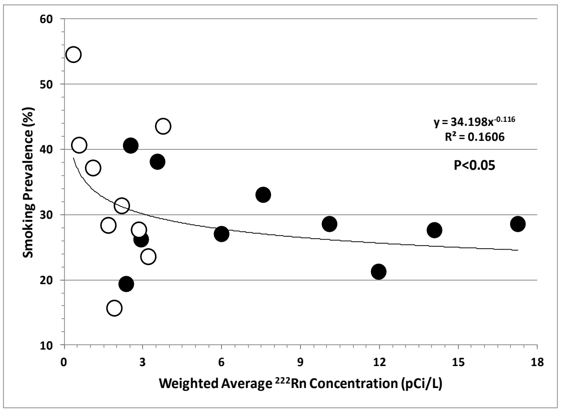

Fig. 4. Scatter plot of smoking prevalence against indoor ^{222}Rn concentrations. Filled and open circles represent data-sets from northern and southern Guam villages respectively. Regression equation and R^2 value shown for line of best fit. 'P' represents significance level of linear correlation coefficient (r=0.401) derived from natural log transformed data-sets.

Considering the well known relationship between smoking and lung cancer, the notable absence of any association between these two variables during the present study may reflect limitations in the smoking prevalence data-sets and/or the survey instrument itself. Either way, the possibility of smoking confounding the relationship between indoor ^{222}Rn and lung cancer on Guam cannot be dismissed out of hand and should be reevaluated as more information comes to light.

3.4. Ethnicity

Ethnic differences in sensitivities to certain chemical and biological agents are well known and are often complicated by interactions between genetic, lifestyle and environmental components. Following their extensive review of the 1998-2002 cancer data for Guam, Haddock et al. reported that age-adjusted lung and bronchus cancer mortalities for Chamorros were disproportionately high (~67 per 100,000 population) compared with Filipinos (~23) and all other Asians (~14)[35]. Haddock subsequently inferred that Chamorros may be genetically more susceptible to lung cancer than other ethnic groups on Guam[36]. In consideration of the fact that Chamorros generally outnumber all other ethnic groups in southern Guam, any increased susceptibility to lung cancer in this group could well have a significant confounding effect on the data presented in Fig 2. To put Haddock's suggestion to the test, we plotted the % of Chamorro lung cancer case per village against % of Chamorro people per village to determine the significance of any overall departure from direct proportionality. Assuming no special genetic sensitivity, the % Chamorros lung cancer cases per village should approximately equal the % Chamorro representation per village (i.e., a 1:1 ratio). The results of this analysis are presented in Fig. 5 and clearly show that Chamorros are no more or less susceptible to lung cancer than other ethnic groups on island, lifestyle and environmental factors notwithstanding.

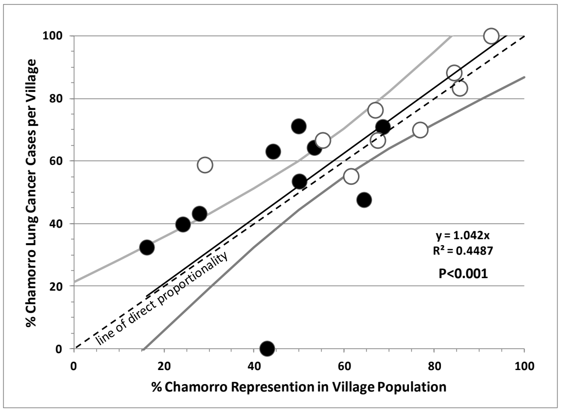

Fig. 5. Scatter plot of % Chamorro lung cancer cases per village against % Chamorros per village population. Filled and open circles represent data-sets from northern and southern Guam villages respectively. Regression equation and R^2 value and 95% confidence limits shown for line forced through zero. 'P' represents significance level of linear correlation coefficient (r=0.670) derived from raw data-sets.

The data for Filipino and all other Asian cancer victims on Guam were analyzed in the same way and with similar results. Both ethnic groups are long-time residents of Guam whose forebears arrived on island shortly after WWII to assist with the rebuilding effort. The Asian community (population: ~10,000) is also largely (95%) confined to the northern half of the island. The Chamorros on the other hand are more widely distributed and are dominant community representatives in the southern villages. It is therefore tempting to speculate here that the ethnic lung cancer disparities noted earlier by Haddock et al.[36] may in fact be linked with geographic differences in radon exposures. The beneficial effects of low-level exposures to ionizing radiation (radiation hormesis) are well known[37-44] although from a regulatory standpoint remain highly controversial[1,45-47]. There is also a growing body of evidence to suggest that indoor radon exposures are not harmful[48,49] and, indeed, may even have a hormetic effect in line with the implications that emerge from of this study[50-56].

3.5. Concluding remarks

The connection between lung cancer and high radon exposures in uranium miners is now well established. This has yet to be convincingly demonstrated for indoor settings despite several claims to the contrary[52, 57-60]. Difficulties in establishing accurate long-term radon exposure records within homes are a major drawback with such studies and the charcoal canister method used by GEPA cannot be expected to provide a realistic estimates of annual exposures[15]. For this reason our weighted average ^{222}Rn estimations should perhaps be regarded with some caution. On the face of it, though, it does seem that the current US EPA action level is overly conservative and needlessly prompting homeowners to install relatively expensive radon reduction systems into building that really don't need them.

The advantages of using 'case-control' exposure studies to determine radon-lung cancer relationships over the more traditional 'ecologic' correlation based study design, like the one used here, are well known[61] although neither approach is without its limitations. We recognize the weaknesses in our study but at the same time consider the strong inverse relationship between lung cancer and radon to be of sufficient interest to warrant further investigation. Moreover, our findings support numerous other studies that challenge the validity of the linear-no-threshold (LNT) model currently adopted by most national and international agencies to determine acceptable risk estimates for lifelong radon exposures. This model assumes that all levels of radiation are potentially harmful, no matter how small - a philosophy that is hotly contested by many[40,47,52,62].

The absence of a radiation threshold below which adverse health effects do not occur is difficult to justify considering that we have evolved on a planet that is continuously generating radiation from within, and are constantly bombarded by cosmic and solar radiation from above. Obviously, the model ignores biological defense and repair mechanisms that prevent countless initiating events from developing into cancers every single day of our lives. The overwhelming number of publications dating back to the 1940s that demonstrate the health benefits of low-level radiation exposures[37,39,49] are also difficult to dismiss. Be that as it may, the LNT model remains the definitive risk assessment tool used in formulating radiation protection policies. Policies that are regarded by some to be an exorbitant waste of public funds in view of the ridiculously low levels of radiation they seek to establish[63]. Clearly, it is time for change.

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