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Field Investigation of the Surface-deposited Radon Progeny as a Possible Predictor of the Airborne Radon Progeny Dose Rate

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Abstract

The quantitative relationships between radon gas concentration, the surface-deposited activities of various radon progeny, the airborne radon progeny dose rate, and various residential environmental factors were investigated through actual field measurements in 38 selected Iowa houses occupied by either smokers or nonsmokers. Airborne dose rate was calculated from unattached and attached potential alpha energy concentrations (PAECs) using two dosimetric models with different activity-size weighting factors. These models are labeled Pdose and Jdose, respectively. Surface-deposited ^{218}Po and ^{214}Po were found significantly correlated to radon, unattached PAEC, and both airborne dose rates ($p < 0.0001$) in nonsmoking environments. However, deposited ^{218}Po was not significantly correlated to the above parameters in smoking environments. In multiple linear regression analysis, natural logarithm transformation was performed for airborne dose rate as the dependent variable, as well as for radon and deposited ^{218}Po and ^{214}Po as predictors. An interaction effect was found between deposited ^{214}Po and an obstacle in front of the Retrospective Reconstruction Detector (RRD) in predicting dose rate ($p = 0.049$ and 0.058 for Pdose and Jdose, respectively) for nonsmoking environments. After adjusting for radon and deposited radon progeny effects, the presence of either cooking, usage of a fireplace, or usage of a ceiling fan significantly, or marginal significantly, reduced the Pdose to 0.65 (90% CI 0.42–0.996), 0.54 (90% CI 0.28–1.02) and 0.66 (90% CI 0.45–0.96), respectively. For Jdose, only the usage of a ceiling fan significantly reduced the dose rate to 0.57 (90% CI 0.39–0.85). In smoking environments, deposited ^{218}Po was a significant negative predictor for Pdose (RR 0.68, 90% CI 0.55–0.84) after adjusting for long-term ^{222}Rn and environmental factors. A significant decrease of 0.72 (90% CI 0.64–0.83) in the mean Pdose was noted, after adjusting for the radon and radon progeny effects and other environmental factors, for every 10 increasing cigarettes smoked in the room. A significant increase of 1.71 in the mean Pdose was found for large room size relative to small room size (90% CI 1.08–2.79) after adjusting for the radon and radon progeny effects as well as other environmental factors. Fireplace usage was found to significantly increase the mean Pdose to 1.71 (90% CI 1.20–2.45) after adjusting for other factors.

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Keywords

radon; progeny; deposition; dose

INTRODUCTION

Over the past 20 years, a number of large population-based epidemiologic studies have been performed in North America, Europe, and China to evaluate the lung cancer risk to the general population from prolonged exposure to residential radon. In summary, the individual studies have generally demonstrated a small, predominantly statistically non-significant, risk between residential radon gas exposure and lung cancer. The recent North American and European pooled residential radon epidemiologic studies reported increased risks of lung cancer, based on measured radon concentration, even below the U.S. Environmental Protection Agency's (EPA's) radon guidance of 150 Bqm^{-3} (Darby et al. 2005; Darby et al. 2006; Krewski et al. 2005; Krewski et al. 2006).

However, the pooled risk estimates were not based on the radon progeny exposure that actually deliver the radiologically significant dose to the lungs, but on radon concentration measurements. If the error associated with the surrogate measure for progeny exposure, radon gas concentrations, does not differ differentially between cases and controls, the observed results tend to be biased towards the null (e.g., finding no association). In fact, we have previously demonstrated that empiric models utilizing improved retrospective radon gas exposure estimates alone, rather than radon concentration, were more likely to detect an association between radon exposure and lung cancer (Field et al. 2002). It follows that retrospective radon progeny exposure estimates would also improve the reliability of the lung cancer risk estimates.

In the late 1980s, it was first proposed that the measurement of surface implanted ^{210}Po could be used as a retrospective monitor for radon exposure (Lively and Ney 1987; Samuelsson 1988). Since then, the techniques and field methods for both accurately measuring the surface implanted ^{210}Po and reconstructing past radon levels in the air from the surface implanted ^{210}Po have been investigated by numerous scientists in both Europe and the U.S. (Birovljev et al. 2001; Cauwels and Poffijn, 2000; Cauwels et al. 2000, Falk et al. 2001; Falk et al.1996; Field et al. 1999; Fitzgerald and McLaughlin 1996; Fleischer and Doremus 2001; Jankowski et al. 1999; Johansson et al. 1994; Lagarde et al. 2002; Lively and Steck 1993; Mahaffey et al. 1996; Mahaffey et al. 1993; Paridaens et al. 2000; Roos and Samuelsson 2002; Roos and Whitlow 2003; Samuelsson 1996; Samuelsson et al. 2001; Samuelsson and Johansson 1994; Samuelsson et al. 1992; Skubalski and Olszewski 1998; Skubalski et al. 2000; Steck et al. 2002; Trotti et al. 1996; Walsh and McLaughlin 2001; Weinberg, 1995). The major research challenge of this technique is reconstructing past airborne radon progeny levels from the measured surface-implanted ^{210}Po including the potential effects of environmental factors.

With the goal of improving radon progeny dose estimates, the Iowa Radon and Lung Cancer Study (IRLCS) and Missouri Radon and Lung Cancer Study-Phase II (MRLCS-II) utilized novel retrospective radon detectors for reconstructing past radon progeny concentrations by analyzing the alpha activity deposited on and implanted in glass surfaces (Lively and Steck 1993; Mahaffey 1999; Mahaffey et al. 1993; Steck and Field 1999; Steck, 1993). The surface-deposited activities of the various radon progeny reflect both the airborne radon progeny activities and atmospheric conditions. IRLCS's Retrospective Reconstruction Detector (RRD) (Lively and Steck 1993; Steck and Field 1999; Steck 1993) incorporates three track registration chips to simultaneously measure contemporary radon gas, contemporary surface-deposited radon progeny, and surface-implanted ^{210}Pb through its alpha emitting progeny ^{210}Po. Theoretically, contemporary airborne radon progeny concentrations can also be estimated through an empirical model using the direct measurements of the short-lived radon progeny that are deposited on surfaces and the radon gas concentration. However, realistically, significant uncertainties exist in the interpretation of the measured contemporary surface-deposited radon progeny and surface-implanted ^{210}Po, because the major room-specific atmospheric factors such as aerosol density and air movement can affect radon progeny deposition appreciably in houses. Due to the uncertainty these factors have on the interpretation, the IRLCS has not moved forward performing risk analyses based on the existing glass-based RRD measurements.

The primary goal of the research described below is to enhance the field calibration of the RRD by characterizing the relationship between the surface-deposited activities of various radon progeny, various residential environmental factors, and the airborne radon progeny dose rate through actual field measurements. The results from our current study will aid in the final reanalysis of the lung cancer risks for the IRLCS based on radon progeny exposure estimates obtained from RRD measurements. In addition, the results of this study will be used as the basis for the future pooled analysis of the Iowa and Missouri Residential Radon Studies, both of which incorporated the use of the glass-based detectors within their study design.

METHODS

Site selection

Radon and radon progeny concentrations were measured from the summer of 2005 to spring 2007 in 38 Iowa houses occupied by either smokers or nonsmokers. Potential participants in eastern Iowa were recruited through a daily news service at the University of Iowa Hospitals and Clinics (UIHC) and a private radon tester in Kalona, Iowa. Screening radon tests using Electret Ion Chambers (Rad Elec Inc., Frederick, Maryland) were performed for selected rooms in the houses of potential participants who agreed to join the study. Homeowners, who occupied their current home for at least seven years and with screening (2 – 4 day test) radon concentrations in the living area greater than 150 $\mathrm{Bqm^{-3}}$, were recruited into the final study. Because of the difficulties recruiting current smokers, eligibility criteria were slightly more relaxed for smokers. Houses of smokers with radon concentrations in the living area exceeding 75 $\mathrm{Bqm^{-3}}$ in screening tests and with current occupancy greater than 5 years were included in the study. Houses were also selected that represented a range of depositional environments (e.g., use of a ceiling circulating fan, fireplace, etc.). A total of 60 houses were screened between the summer of 2005 and spring of 2007. Based on the above parameters, 38 houses in 13 cities or towns within the state of Iowa were selected for the final study. In each of the 38 houses, two frequently occupied rooms with an appropriate glass object for measurement were identified as study units. Active smoking was present in 18 houses.

Description of radon and radon progeny detectors

All of the novel radon or radon progeny detectors utilized in this project were fabricated and calibrated in the physics laboratory of one of the authors (DJS).

Retrospective radon detector (RRD)—The RRD utilized in this study is a track registration CR-39 chip held in a 35mm×35mm slide mounted with an 18mm×22mm opening. It incorporates energy absorbing strips in a landscape (horizontal) orientation. The two sides of the detector act as independent detecting surfaces as shown in Figure 1. The side facing into the room is designed to record the alpha particles emitted from the surface-deposited radon progeny. This side has two areas covered by energy-absorbing filters of different thickness; one is sensitive to 214Po, which emits a 6.00 MeV alpha, and the other records both 214Po and 218Po, which emits a 7.69 MeV alpha. The side facing the glass is designed to record the alpha particles emitted from the implanted radon progeny in glass. This side has two areas covered by aluminized Mylar. The bottom portion of the side is also covered by a polyester film that makes that area much more sensitive to ^{210}Po than it is to the natural alpha emitting contaminants in glass. The whole detector assembly is attached to the selected glass by a 3M outdoor mounting tape tab.

Airborne radon progeny detector (ARPD)—The ARPD is a detector that actively samples the room air and measures the short-lived alpha emitting radon progeny ^{214}Po and ^{218}Po with track registration material (Fig. 2). Since the aerosol size distribution is an important factor in determining the radon progeny dose estimation, the ARPD is designed to distinguish two size fractions: unattached (up to 5 nm) and attached (>5 nm). Within the ARPD, the unattached radon progeny are collected by the screen, while the attached are collected by the filter. The CR-39 chip holder is located 1 cm above the screen or filter. The chip is covered by two strips of polyester film, each defining either the ^{214}Po sensitivity area or the ^{214}Po and ^{218}Po sensitivity area.

Radon/thoron gas detector (GD)—The radon/thoron gas detector contains two separate passive alpha track detectors (ATD) that measure radon and thoron gas respectively. Each ATD contains a CR-39 track registration chip housed in a 5cm × 5cm cylinder. The ATD, which is sensitive only to radon, is sealed in a polyethylene bag. Thoron concentrations are calculated from the difference between the tracks in the two ATD units (Steck 2006).

Radon and radon progeny measurements

Glass objects selected for measurement of surface-deposited radon progeny met the following criteria: 1) the glass surface must be ‘ordinary’, smooth glass without visible coatings or colorings (not lead crystal); 2) the glass should be vertically mounted and facing the interior of the room; 3) the glass surface must have a known age; 4) the glass surface should be large enough to collect sufficient total activity. Based on these criteria, appropriate glass objects were selected in the eligible house for measurement. Additional details concerning glass selection are found elsewhere (Field et al. 1999). After the proper glass object was identified, the deposited alpha activities and the implanted activities were measured using an RRD applied to the glass for 90 days; and simultaneously, the radon and thoron gas concentrations were measured using a GD as illustrated in Figure 3. Toward the end of the 90-day measurement period, the airborne radon progeny, by species and bimodal size fraction, were measured using an ARPD for 3 to 7 days along with concurrent measurement of radon gas using EICs.

Collecting pertinent “non-radiation” data

Information regarding the age of the house and years of current owner’s occupancy was collected for each study site. Room specific information was collected either by facilitating a face-to-face questionnaire or by direct ascertainment when possible. Room information included: room type and room location within the house, room size, room ventilation mechanisms, room cooling and heating systems, frequency of smoking within the room, presence of other aerosol sources and aerosol sinks (e.g., cooking, candle, fireplace, humidifier, freshener, air cleaner), and selected glass surface information (type, age, cleaning frequency, film, obstacle and air flow rates vertical/horizontal/normal to the surface). Figure 4 shows a typical study room where both “radiation” and “non-radiation” data were collected.

Detector processing, reading, and results translation

The CR-39 chips from the RRD, ARPD, and GD were disassembled in the laboratory and developed at 75°C ±3°C in a 6.25N NaOH solution for 6 hours. Next, the number of alpha tracks on the track-bearing areas of each chip was visually counted, using a microscope at 100X, until at least 150 tracks in three or more distinct regions were counted. The number of alpha tracks counted was then converted to tracks/mm^2 and divided by the exposure duration of each detector. Finally, the track densities were translated into radon or radon progeny activities and potential alpha energy concentrations (PAEC) with the calibration factors previously developed by one of the authors (DJS).

Effective lung dose estimates

The deposition of radon decay products is not equal in each of the respiratory regions. The bronchial region receives the major proportion of the total lung dose in the size range of cluster mode (<5 nm), while the bronchiolar region receives the highest dose in the size range of the aerosol attached mode (>10 nm) (Porstendorfer 2001). Even in the size range from 10–100 nm, where the alveolar region has relatively higher particle deposition efficiency, the effective dose contribution of this region is more than five times lower than the contribution of the bronchial and bronchiolar region (Porstendorfer 2001). In addition, 90–95% of malignant primary lung tumors are bronchogenic (Porstendorfer 2001). Taking into account the data regarding cancer of the human respiratory tract, PorstendÖrfer (2001) set the relative sensitivity between bronchial (WBB), bronchiolar (Wbb), and alveolar-interstitial (WAI) lung region as WBB:Wbb:WAI = 0.80:0.15:0.05. This partitioning of detriment leads to higher effective doses by the decay product clusters (unattached fraction) and lower values by the aerosol fraction than the partitioning WBB:Wbb:WAI = 0.33:0.33:0.33 recommended by ICRP 66 and revisited by James et al. (2004). Patton (2005) summarized the James and Porstendörfer effective dose conversion coefficients as shown in Table 1. In this paper, we call the effective dose calculated from the dose conversion factors recommended by Porstendörfer and James “Pdose” and “Jdose”, respectively.

Data analyses

Correlation analyses were used to estimate the correlations among the measured radon, airborne bimodal PAECs, dose rates and surface-deposited radon progeny. Multiple linear regression models were used to identify a quantitative relationship between the airborne radon progeny dose rate and the surface-deposited radon progeny as well as to estimate the effect of important indoor environmental factors. Because the radon concentrations, airborne dose rates, and surface-deposited radon progeny activities are all highly right-skewed, natural logarithm transformations were applied to allow analysis by parametric regression. The normality of each of the above variables was checked before and after natural logarithm transformation. Model selection, based on the adjusted R-square, was conducted to choose the best surface-deposited radon progeny or combinations in predicting dose rate. In addition, backward variable selection method, which starts with the complete model and backward eliminates the least significant variable repeatedly, was used to choose other potential environmental predictor variables for inclusion. Variables with p-values < 0.20 were kept in the variable selection. Analyses were carried out using SAS statistical software (SAS Institute Inc., Cary, NC, USA).

Since the behavior of the radon progeny is highly related to aerosol density and smoking is the most effective indoor aerosol source, all analyses were conducted separately for smoking rooms and nonsmoking rooms. In this study, “smoking rooms” were defined as any room in which an individual currently smokes at least two cigarettes each day. Another important reason for grouping by smoking status is that smokers’ houses tended to have lower radon concentrations likely because of the relaxed inclusion criteria for homes with active smoking.

RESULTS

During the course of the measurement study from the summer of 2005 to the spring of 2007, a complete set of radon/radon progeny and environmental factors measurements were collected for a total of 76 rooms from the 38 Iowa houses. Among the 76 rooms, 22 rooms from 11 houses were selected for repeat measurement during different seasons based in part on the homeowners' willingness to allow additional testing. The original measurements were carried out in the winter of 2005 and the repeat measurements were carried out in the summer of 2006 for these 22 rooms. Information on all environmental factors included in the original measurement period was collected during the repeat measurement period as well.

Because the primary research interest in this paper is to study the physical behavior of radon progeny within each room through simultaneous measurements of both airborne and surface-deposited radon progeny, all 98 sets of data were included for the final analysis. Unfortunately, 26 of the 98 data sets were excluded from the regression analysis involving surface-deposited radon progeny because the measured ^{218}Po surface activities were negative for those rooms. The negative results could have occurred in low-deposition environments due to random track density variations in the two alpha registration areas of the RRD detector used to estimate ^{218}Po activity and uncertainties in RRD calibrations.

Descriptive statistics

The descriptive statistics for major physical parameters measured are summarized, by smoking status, in Table 2. The short-term ^{222}Rn refers to the radon concentrations measured using EICs simultaneously with the ARPD, while the long-term ^{222}Rn refers to the radon concentrations measured using GD simultaneously with RRD. As expected, the means for both the short-term ^{222}Rn and long-term ^{222}Rn from smoking rooms are much lower than those from nonsmoking rooms most likely due to the different recruiting criteria for smokers and nonsmokers previously described. The equilibrium factor (F) and unattached fraction (fp), which should have no relation with radon concentration, were negatively related as expected (Figure 5). Smoking increases the aerosol concentration in the room, thus almost all of the radon progeny is attached to aerosol, so the unattached fraction of radon progeny fp will decrease. Smoking was positively related to F and negatively related to fp.

The descriptive statistics for major environmental factors are summarized in Table 3. The median occupant residency in current homes was 12.5 years and the median age of the houses was 43 years.

Correlation analysis

Table 4 presents the Spearman correlation coefficients between airborne and deposited measurements by smoking status.

In nonsmoking rooms, both deposited ^{218}Po and deposited ^{214}Po activities exhibited very good correlation with short-term ^{222}Rn, long-term ^{222}Rn, airborne unattached PAEC, Pdose, and Jdose ($p < 0.0001$). Only the airborne attached PAEC was not significantly correlated with deposited radon progeny. The lower deposition velocity for large size particles could well explain this phenomenon. For airborne dose rate, the correlation between Pdose and the deposited radon progeny is slightly better than that between Jdose and deposited radon progeny, because Pdose puts higher weight on unattached fraction of PAEC.

In smoking rooms, which represent a low deposition environment, none of the Spearman correlations between deposited ^{218}Po and airborne parameters was significant at the 0.05 level. Alternatively, the correlations between deposited ^{214}Po and airborne parameters remain statistically significant with the exception of the attached PAEC.

Regression analyses

In order to fulfill the assumption of multiple linear regression method, the dependent variable (in our study, Pdose and Jdose) has to be normally distributed. A Shapiro-Wilk test was used to assess the normality. After the natural logarithm transformation, tests for both ln Pdose and ln Jdose failed to reject the normality hypothesis at the 0.05 level of significance (ln Pdose: $p = 0.34$, ln Jdose: $p = 0.07$), which indicated that ln Pdose and ln Jdose could be treated as normally distributed and thus eligible to be dependent variables in the multiple linear regression (Figure 6 and Figure 7). Although there was no normality requirement for the explanatory variables, normality or near normality of explanatory variables will improve the accuracy of the regression parameters. Normality was also tested for ln long-term ^{222}Rn, ln deposited ^{218}Po, and ln deposited ^{214}Po with p-values 0.0024, 0.0898 and 0.8898, respectively. In the following regression analyses, long-term ^{222}Rn, deposited ^{218}Po, and deposited ^{214}Po are all in natural logarithm scale.

Regression analyses were divided into two steps. First, only long-term ^{222}Rn, deposited ^{218}Po, and deposited ^{214}Po were considered as potential predictors of airborne dose rate (Pdose and Jdose). The selection results based on the adjusted R-square are presented in Table 5. When the backward variable selection method was used, it produced the same selection results as the adjusted R-square (Table 5). The adjusted R-square for short-term ^{222}Rn was also used for comparison with long-term ^{222}Rn. The higher correlation between dose rate and short-term ^{222}Rn as compared to long-term ^{222}Rn likely reflects the fact that the dose rate and short-term ^{222}Rn were measured simultaneously for 3–7 days during the end of the 90-day long-term measurements. For nonsmoking rooms, the combination of long-term ^{222}Rn and deposited ^{214}Po performed the best for predicting both Pdose and Jdose. For smoking rooms, the combination of long-term ^{222}Rn, deposited ^{218}Po, and deposited ^{214}Po performed the best in predicting Pdose, while the combination of long-term ^{222}Rn and deposited ^{218}Po was the best choice for predicting Jdose.

Backward variable selection was used to choose environmental factors that have potential influence on the relationship between airborne dose rate and deposited radon progeny. The *a priori* selected environmental factors for this analysis were room size (large or small), presence/absence of cooking, presence/absence of fireplace usage, presence/absence of candle burning, presence/absence of air cleaner usage, presence/absence of window opening, presence/absence of central air system, presence/absence of fan usage, presence/absence of obstacles in front of the RRD, and the presence of dust film on the glass surface on a scale of 0–10.

Four separate models were built for Pdose and Jdose and by different smoking status. When selecting the environmental factors, the best combinations of radon and deposited radon progeny determined in the first step were included in each regression model. The results of the model selection for Pdose are shown in Table 6 and the results for Jdose are presented in Table 7.

For both Pdose and Jdose, under both smoking and nonsmoking conditions, the long-term ^{222}Rn was a significantly positive predictor, at the 0.10 significance level, for dose rate after adjusting for all other covariates in the model (Table 6 and Table 7).

In nonsmoking environments, for both Pdose and Jdose, a significant interaction effect was detected, at the 0.10 level, between deposited ^{214}Po and an obstacle in front of the RRD in predicting dose rate ($p = 0.049$ and 0.058 for Pdose and Jdose, respectively). When there was no obstacle in front of the RRD, the ln deposited ^{214}Po was positively related to ln Pdose. Alternatively, when an obstacle existed, no observable relationship was detected between deposited ^{214}Po and ln Pdose (Figure 8). The same findings were noted for Jdose. Presence of cooking, fireplace usage, or ceiling fan usage reduced, either significantly or with marginal significance, the Pdose after adjusting for other predictors in the model including the interaction effect between deposited ^{214}Po and an obstacle. For example, the presence of cooking in the room significantly reduced the Pdose to 0.65 (90% CI 0.42–0.996). For Jdose, only the presence of fan significantly reduced the dose rate to 0.57 (90% CI 0.39–0.85).

In smoking environments, deposited ^{218}Po was a significant negative predictor for Pdose (RR 0.68, 90% CI 0.55–0.84) after adjusting for long-term ^{222}Rn and environmental factors. After adjusting for the radon and radon progeny effects and other environmental factors, for every 10 increasing cigarettes smoked in the room, a significant decrease of 0.72 (90% CI 0.64–0.83) in the mean Pdose was noted. After adjusting for the radon and radon progeny effects and other environmental factors, a significant increase of 1.71 in the mean Pdose was found for large room size relative to small room size (90% CI 1.08–2.79). After adjusting for the radon and radon progeny effects and other environmental factors, the presence of fireplace usage was found to significantly increase the mean Pdose to 1.71 (90% CI 1.20–2.45). Very similar results were also found for Jdose.

DISCUSSIONS AND CONCLUSIONS

From the multiple regression analyses, we found that the surface-deposited radon progeny were useful in predicting airborne dose rate even after adjusting for the radon gas effect in both nonsmoking and smoking environments. In the nonsmoking environment, Pdose exhibited greater sensitivity to additional aerosol sources like cooking and fireplace as compared to Jdose, because Pdose was weighted more toward the unattached fraction of PAEC that would be reduced by the presence of additional aerosol sources. In addition, the usage of a fan was found to effectively reduce both Pdose and Jdose by accelerating radon progeny deposition and exhaust in the nonsmoking environment. In the smoking environment, as the number of cigarettes smoked in the room increased, both Pdose and Jdose decreased. This finding likely reflects the higher attachment rate of radon progeny, due to an increase in aerosol density, resulting in lower effective dose conversion factors. After adjusting for the effect of smoking, fireplace usage became a positive predictor for both Pdose and Jdose. The fact that larger room sizes have smaller surface-to-volume ratios and thus lower deposition rates, for both unattached and attached radon progeny, likely contributes to the positive effect of room size on both Pdose and Jdose.

The interaction effect between obstacles in front of the glass and the deposited radon progeny in predicting airborne dose rate indicates interpretation of these measurements require careful scrutiny prior to use in any retrospective dose assessment. In addition, future epidemiologic studies involving radon progeny exposure assessment using RRDs should avoid the use of any glass surfaces with objects that may impede the normal deposition of particles.

Because the study houses were selected based on convenience rather than a random sample of Iowa houses, a potential limitation of the study is the generalizability of the study results to a wide cross-section of homes. It is unknown how well the selected homes represent the general housing stock in the upper Midwest. Nevertheless, the study was focused on objective measurements of radon and radon progeny as well as related environmental factors including fan usage, heating type, etc. The heating/ventilating/air conditioner (HVAC) system used in most homes of the current study represents the major air ventilation type in the upper Midwest. In the current field study, 81.6% of the houses had forced HVAC systems, which is fairly reflective of the percent (80.4%) of the control homes in the original IRLCS (Field et al. 2000).

From the measurement perspective, a potential bias might be introduced by the fact that the ARPD only measures a small portion of the entire measurement period of the RRD. Because long-term active airborne radon progeny concentrations cannot be measured inexpensively and accurately with current technology, we were only able to perform short-term active airborne radon progeny measurements. In addition, in order to minimize the travel time to the test homes, the ARPD measurements were usually performed toward the end of the 90 days so that all the field measurements, including the RRDs, could be finished at the same time. The last 3 to 7 days of the 90 days may not represent the typical patterns of weather and related heating/cooling system usage in the house. Differences in the depositional environment and radon concentrations over the 90 day study period as compared to the final 3 to 7 days may introduce further error when matching the results from the RRD and ARPD. Nevertheless, measurements of the actual airborne radon progeny activity represent a significant advance over previous epidemiologic studies or field investigations. Because the majority of information on the environmental factors (e.g., smoking frequency) that could influence the radon and radon progeny measurements was obtained by questionnaire, both recall bias and information bias may have occurred. In addition, some environmental factors like aerosol conditions and ventilation usage were constantly changing from time to time during the 90-days study period, which may have introduced additional error. However, to assess the reliability of the collected information, the same questions on smoking and other important environmental factors were asked at the start of the study and then asked again at the end of the 90 days. We noted that the agreement between the collected environmental information was quite good between the first and second time points.

The complex relationship between radon and the fate of its progeny has not been studied in many U.S. homes. While the progeny activity size distribution was tracked for short periods in two eastern homes (Hopke 1995), only grab sample measurements in 40 additional New York and New Jersey homes provide the basis for establishing the “typical” radon to progeny relationship (James et al. 2004; USEPA 1992). Our results provide both short-term and long-term data from a sample of 38 homes from the U.S. Midwest with a wide variety of environmental conditions. The good correlation between short-term airborne progeny dose and surface deposited progeny activity in these homes suggest that contemporary and retrospective radon dosimetry can be improved to better estimate the lung cancer risk posed by protracted residential radon progeny exposure.

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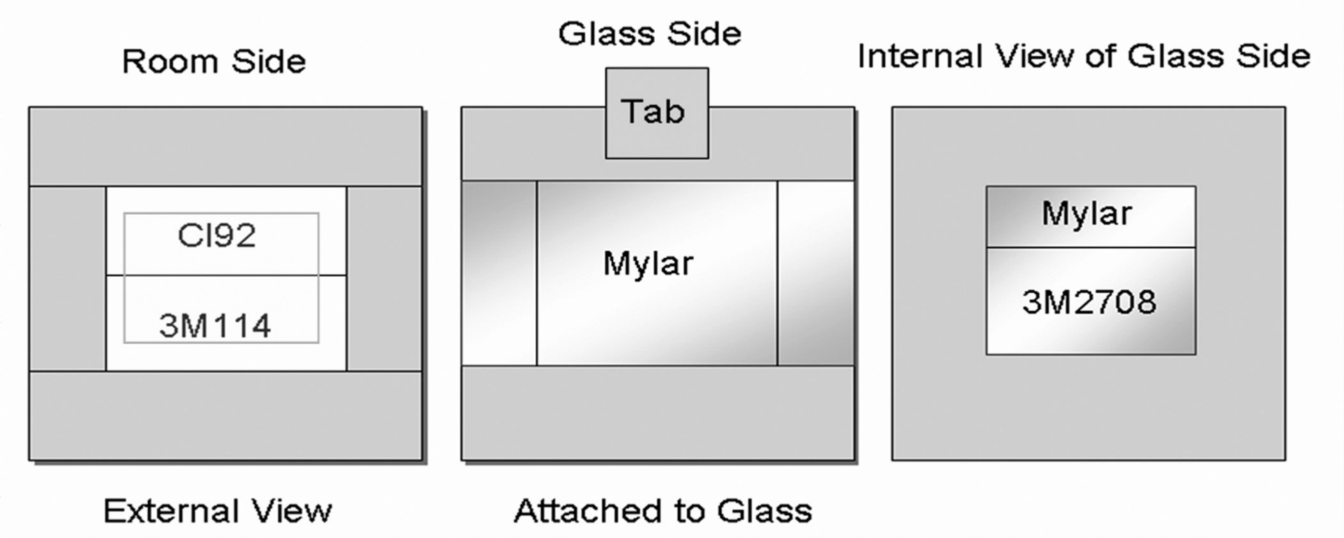

Figure 1.
Schematic drawing of the RRD

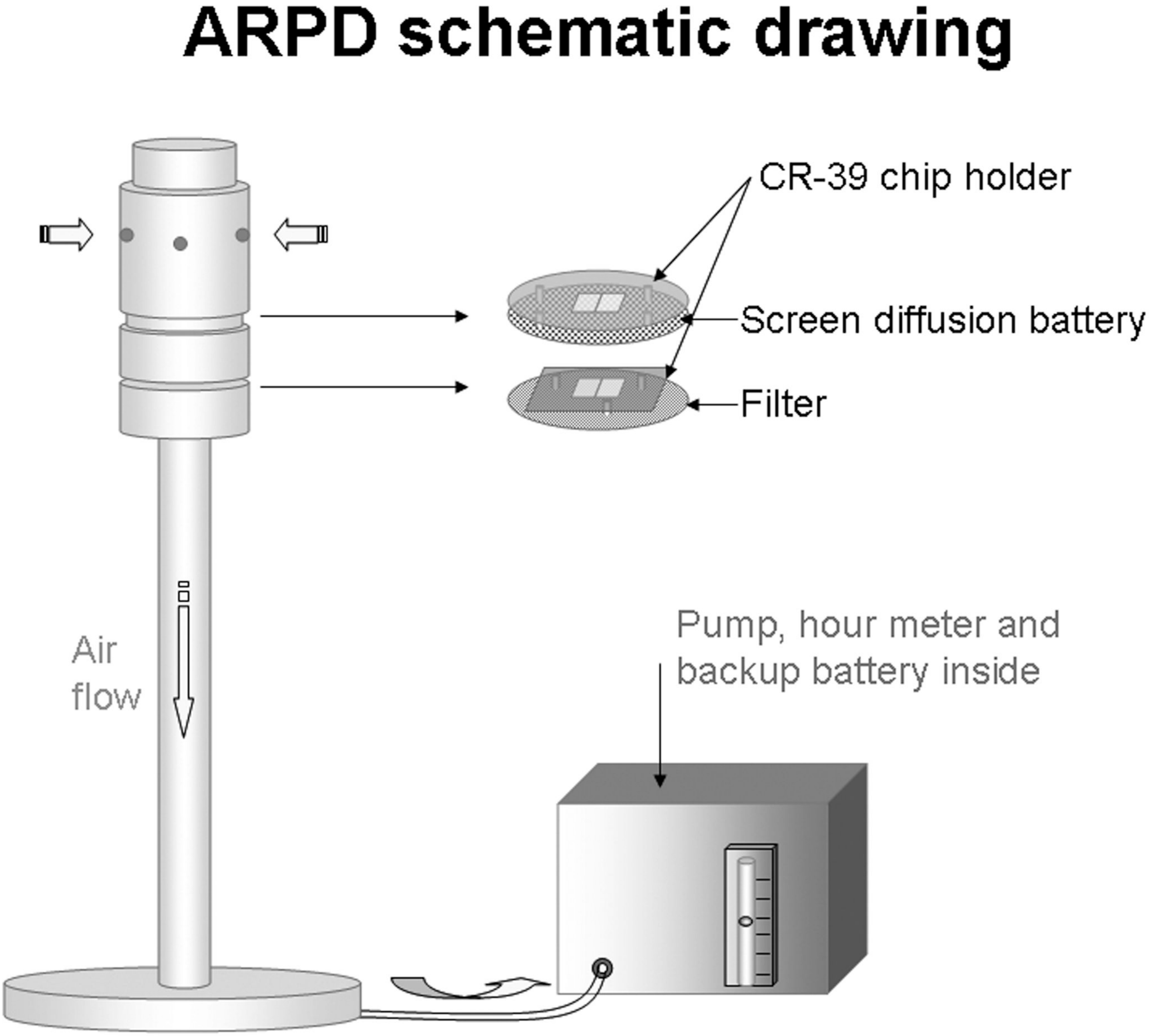

Figure 2.
Schematic drawing of the ARPD

Figure 3.
The glass-based RRD and radon/thoron gas detectors are simultaneously exposed for 90 days in a selected room

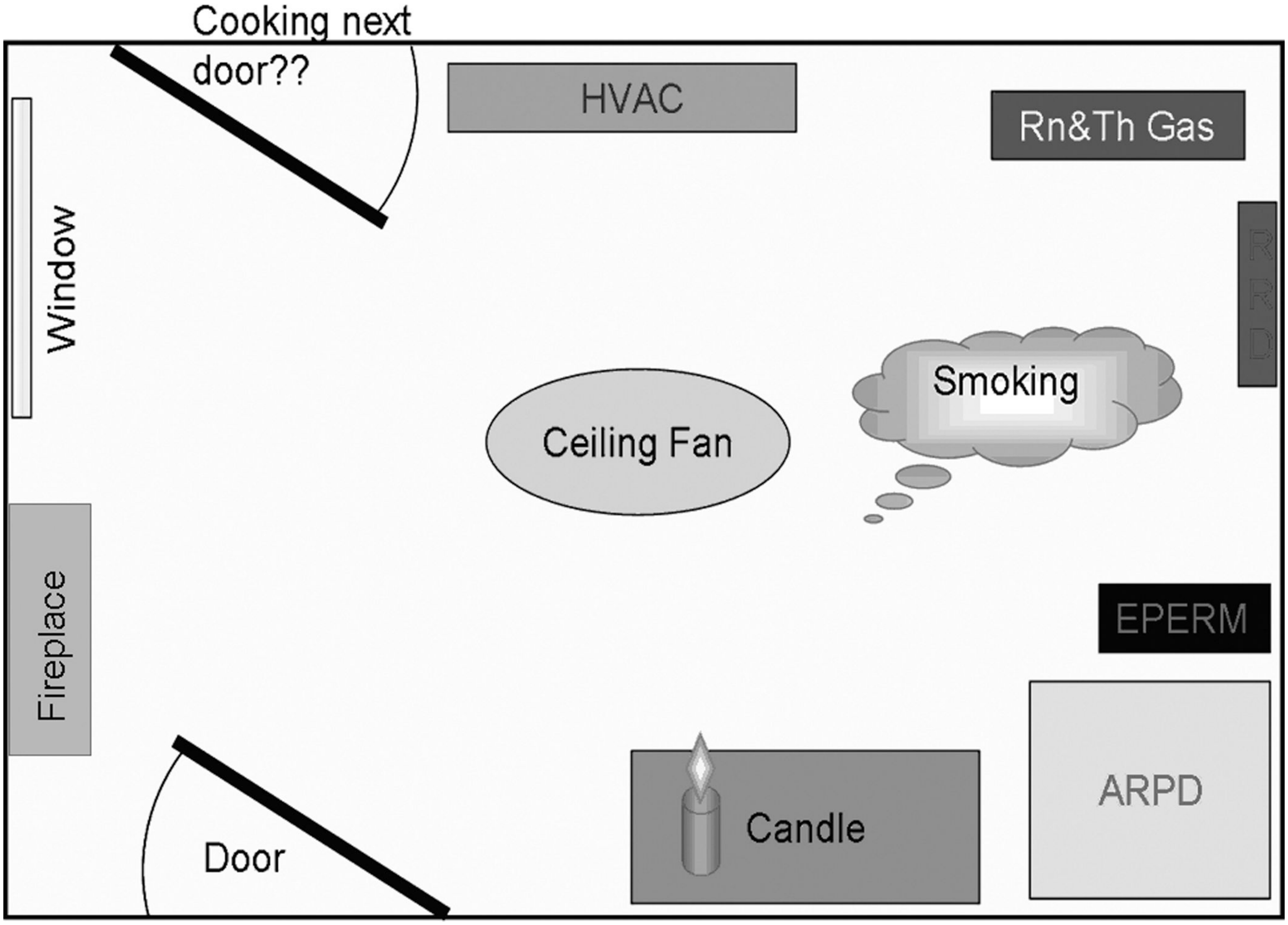

Figure 4.
A typical study room with radon/radon progeny detectors and relevant environmental factors distribution

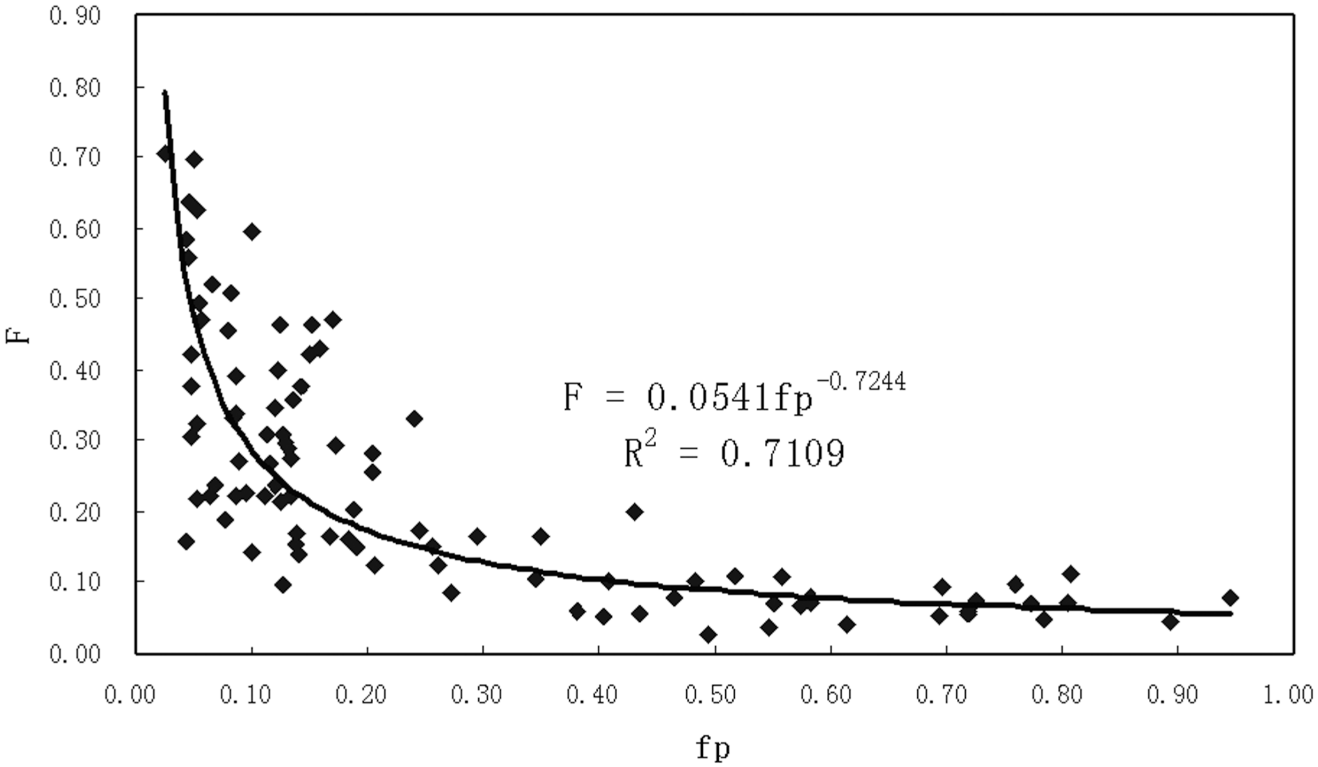

Figure 5.

The relationship between equilibrium fraction F and unattached fraction fp

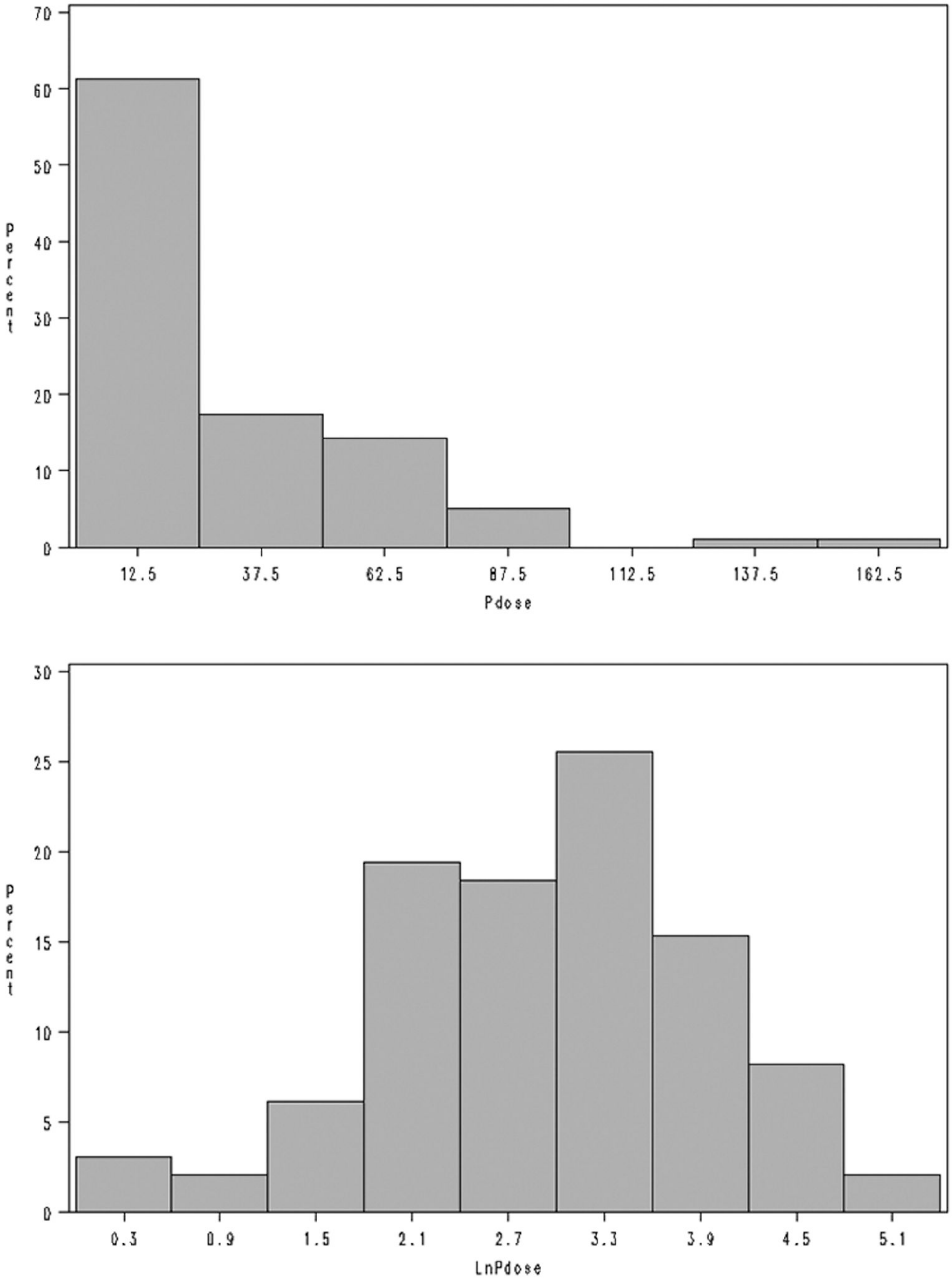

Figure 6.

Histograms of Pdose before and after log transformation

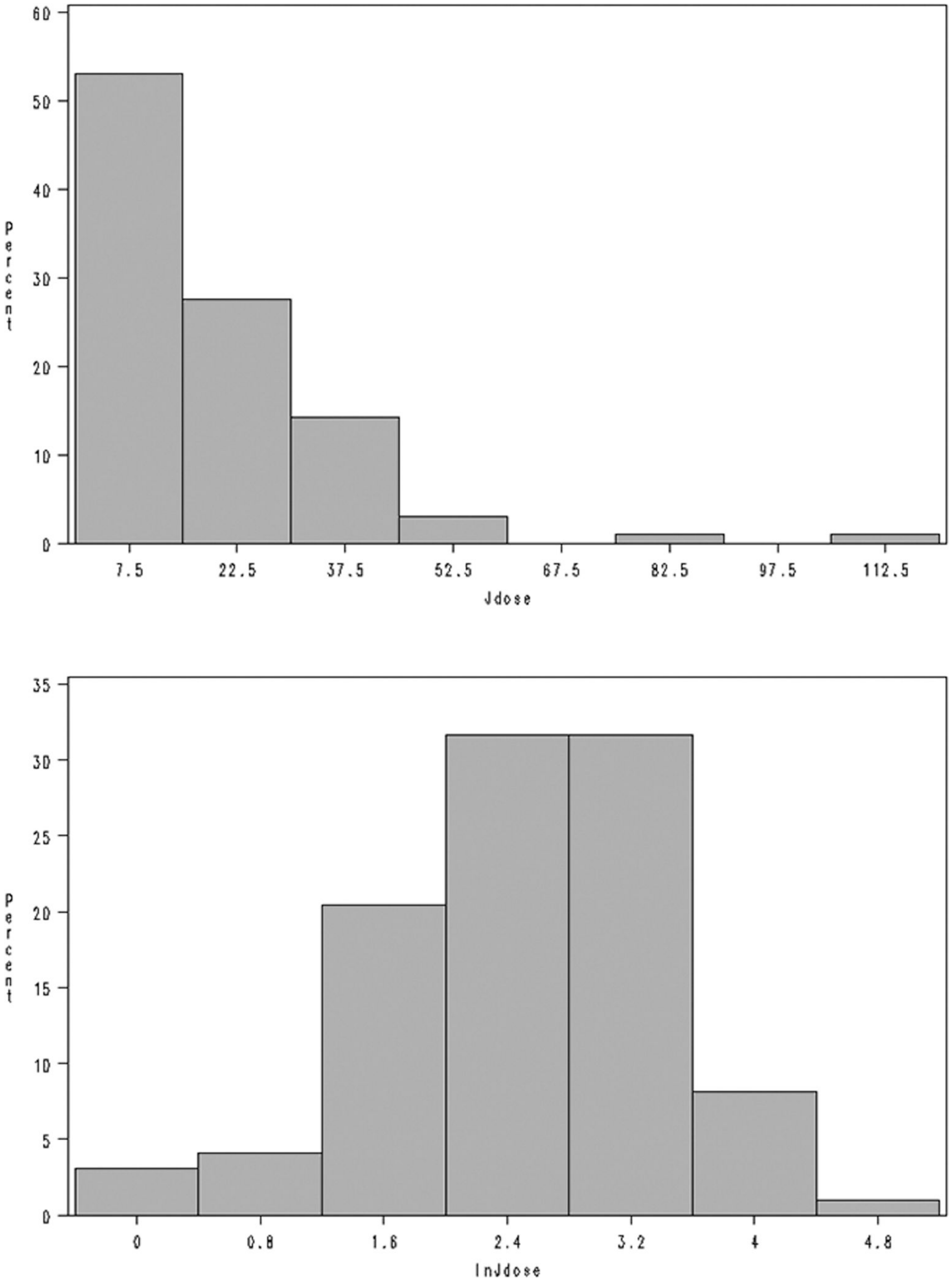

Figure 7.

Histograms of Jdose before and after log transformation

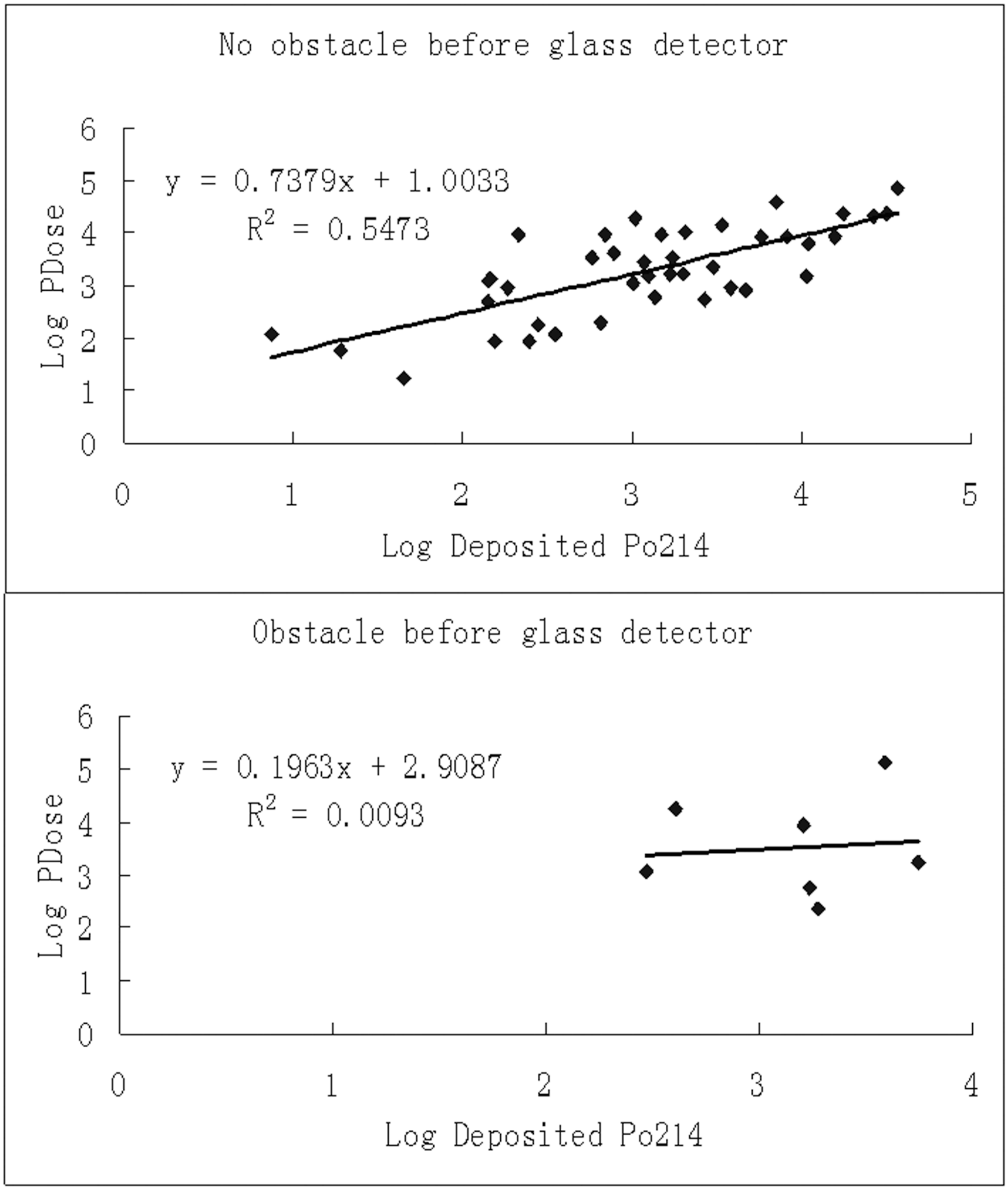

Figure 8.

The interaction effect between obstacles and deposited 214Po in predicting airborne Pdose

Table 1

Calculated effective dose conversion factors (DCF)

Effective DCFs ($mSvyr^{-1}WLM^{-1}$)	**0.6–5 nm**	**5–1400 nm**
James	85	10.1
Porstendörfer	186	4.8

Table 2

Descriptive statistics for measured radon, airborne PAECs, dose rates, F, fp and surface deposited radon progeny by smoking status

Variables	Environment (n)	Range	Median	Mean (SD)	Unit
Short-term ^{222}Rn	Nonsmoking (62)	33–940	285	317 (218)	
	Smoking (36)	11–429	141	159 (111)	Bqm^{-3}
	Total (98)	11–940	205	259 (200)	
Unattached PAEC	Nonsmoking (62)	0.4–14.6	2.6	3.5 (3.0)	
	Smoking (36)	0.2–5.2	1.0	1.2 (1.0)	mWL
	Total (98)	0.2–14.6	1.6	2.7 (2.7)	
Attached PAEC	Nonsmoking (62)	0.3–101.5	6.5	12.7 (16.6)	
	Smoking (36)	0.1–53.6	9.4	13.6 (13.4)	mWL
	Total (98)	0.1–101.5	8.1	13.1 (15.4)	
Pdose	Nonsmoking (62)	3.5–166.1	26.2	37.4 (31.4)	
	Smoking (36)	1.5–54.9	11.9	14.9 (11.6)	$mSvyr^{-1}$
	Total (98)	1.5–166.1	20.9	29.1 (28.1)	
Jdose	Nonsmoking (62)	1.7–117.7	16.2	22.3 (19.7)	
	Smoking (36)	0.7–42.0	8.5	12.4 (10.1)	$mSvyr^{-1}$
	Total (98)	0.7–117.7	13.5	18.7 (17.5)	
F	Nonsmoking (62)	0.03–0.62	0.16	0.20 (0.16)	
	Smoking (36)	0.06–0.70	0.30	0.32 (0.18)	
	Total (98)	0.03–0.70	0.22	0.25 (0.17)	
Fp	Nonsmoking (62)	0.04–0.95	0.21	0.34 (0.26)	
	Smoking (36)	0.02–0.72	0.09	0.18 (0.18)	
	Total (98)	0.02–0.95	0.15	0.28 (0.25)	
Long-term ^{222}Rn	Nonsmoking (62)	19–740	250	272 (172)	
	Smoking (36)	4–474	159	184 (105)	Bqm^{-3}
	Total (98)	4–740	218	239 (157)	
Deposited ^{218}Po	Nonsmoking (48)	0.5–269.7	23.4	40.8 (48.3)	
	Smoking (24)	5.8–71.6	17.6	23.0 (18.7)	Bqm^{-2}

Variables	Environment (n)	Range	Median	Mean (SD)	Unit
	Total (72)	0.5–269.7	20.4	34.8 (41.5)	
Deposited ^{214}Po	Nonsmoking (48)	2.4–95.9	24.2	29.5 (22.5)	
	Smoking (24)	4.7–51.7	14.1	17.0 (10.6)	Bqm^{-2}
	Total (72)	2.4–95.9	19.2	25.3 (20.2)	

Table 3

Descriptive statistics for environmental categorical variables

Variable	Levels	N	Percents
Season	spring	29	38
	summer	15	20
	winter	32	42
Room type	basement	4	5
	bedroom	12	16
	dinning room	6	8
	entertainment room	3	4
	family room	12	16
	hallway	1	1
	kitchen	5	7
	living room	28	37
	work room	5	7
Room size	small	27	36
	large	49	64
Room level	basement	23	30
	first floor	49	64
	second floor	4	5
Smoking	no	44	58
	yes	32	42
Cooking	no	66	87
	yes	10	13
Candle	no	46	61
	yes	30	39
Fireplace	no	64	84
	yes	12	16
Humidifier	no	72	95
	yes	4	5
Air cleaner	no	74	97
	yes	2	3
Open window	no	53	70
	yes	23	30
HVAC	none	13	17
	forced air	62	82
	window AC	1	1
Fan usage	none	58	76
	ceiling fan	14	18
	floor fan	2	3
	other fan	2	3

Note: HVAC=heating, ventilation and air conditioner

Table 4

Spearman correlation coefficients and p-values under zero-correlation null hypothesis between airborne and deposited measurements by smoking status

		Deposited radon progeny	
Environment	**Airborne measurements**	**^{218}Po**	**^{214}Po**
Nonsmoking (48)	Short-term ^{222}Rn	0.58 <.0001	0.73 <.0001
	Long-term ^{222}Rn	0.62 <.0001	0.75 <.0001
	Unattached PAEC	0.61 <.0001	0.64 <.0001
	Attached PAEC	0.20 0.1701	0.11 0.4417
	Pdose	0.59 <.0001	0.61 <.0001
	Jdose	0.53 <.0001	0.53 0.0001
	Deposited ^{218}Po		0.58 <.0001
Smoking (24)	Short-term ^{222}Rn	0.06 0.7789	0.56 0.0047
	Long-term ^{222}Rn	0.28 0.1808	0.70 0.0001
	Unattached PAEC	−0.14 0.5288	0.51 0.0109
	Attached PAEC	0.14 0.5022	0.22 0.3015
	Pdose	−0.04 0.8655	0.51 0.0116
	Jdose	−0.04 0.8655	0.51 0.0116
	Deposited ^{218}Po		0.26 0.2279

Table 5

Adjusted R-square from the natural log-scale[a] multiple regression results for deposited radon progeny in comparison to radon

Environment	**Dose being predicted**	**Short-term ^{222}Rn[b]**	**Long-term ^{222}Rn[c]**	**Long-term ^{222}Rn and deposited ^{214}Po[c]**	**Long-term ^{222}Rn and deposited ^{218}Po[c]**	**Long-term ^{222}Rn and deposited ^{214}Po, ^{218}Po[c]**
Nonsmoking	Pdose	0.71	0.43	***0.51***[d]	0.44	0.50
	Jdose	0.68	0.37	***0.43***	0.36	0.42
Smoking	Pdose	0.82	0.32	0.33	0.39	***0.42***
	Jdose	0.86	0.29	0.26	***0.32***	0.30

[a] All dependent variables and explanatory variables in the regression analysis are in natural log-scale.

[b] The whole data set (Total=98, Nonsmoking=62, Smoking=36) was used.

[c] The valid deposited radon progeny data set (Total=72, Nonsmoking=48, Smoking=24) was used.

[d] The bold italics values indicate the adjusted R-square for the best model selected.

Table 6

Estimated relative mean change in Pdose for selected predictors using multiple regression analysis by smoking status

Environment	Predictor	(N)	Relative mean Pdose (90% CI)[a]
Nonsmoking	Ln Long-term ^{222}Rn (unit 1 increase)	(48)	1.57 (1.19–2.07)
Obstacle=0	Ln Deposited ^{214}Po (unit 1 increase)	(41)	1.62 (1.31–2.01)
Obstacle=1	Ln Deposited ^{214}Po (unit 1 increase)	(7)	0.12 (0.02–0.58)
	Cooking	(48)	
	Present	(5)	0.65 (0.42–0.996)
	not present	(43)	1.00[b]
	Fireplace	(48)	
	Present	(2)	0.54 (0.28–1.02)
	not present	(46)	1.00[b]
	Fan	(48)	
	Present	(8)	0.66 (0.45–0.96)
	not present	(40)	1.00[b]
Smoking	Ln Long-term ^{222}Rn (unit 1 increase)	(24)	2.28 (1.85–2.80)
	Ln Deposited ^{218}Po (unit 1 increase)	(24)	0.68 (0.55–0.84)
	Number of cigarette (10 increase)	(24)	0.72 (0.64–0.83)
	Size	(24)	
	Large	(16)	1.47 (1.09–1.99)
	Small	(8)	1.00[b]
	Fireplace	(24)	
	Present	(5)	1.71 (1.20–2.45)
	not present	(19)	1.00[b]

[a] The relative mean change in Pdose after adjusting for all other covariates in each smoking status.

[b] Reference category

Table 7

Estimated relative mean change in Jdose for selected predictors using multiple regression analysis by smoking status

Environment	Predictor	(N)	Relative mean Jdose (90% CI)[a]
Nonsmoking	Ln Long-term ^{222}Rn (unit 1 increase)	(48)	1.56 (1.16–2.09)
Obstacle=0	Ln Deposited ^{214}Po (unit 1 increase)	(41)	1.51 (1.22–1.88)
Obstacle=1	Ln Deposited ^{214}Po (unit 1 increase)	(7)	0.16 (0.02–1.22)
	Fan	(48)	
	Present	(8)	0.57 (0.39–0.85)
	xnot present	(40)	1.00[b]
Smoking	Ln Long-term ^{222}Rn (unit 1 increase)	(24)	2.42 (1.79–3.26)
	Ln Deposited ^{218}Po (unit 1 increase)	(24)	0.69 (0.51–0.94)
	Number of cigarette (10 increase)	(24)	0.74 (0.61–0.89)
	Size	(24)	
	Large	(16)	1.55 (1.00–2.40)
	Small	(8)	1.00[b]
	Fireplace	(24)	
	Present	(5)	1.75 (1.04–2.96)
	not present	(19)	1.00[b]

[a] The relative mean change in Jdose after adjusting for all other covariates in each smoking status.

[b] Reference category