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A COMPARISON OF WINTER SHORT-TERM AND ANNUAL AVERAGE RADON MEASUREMENTS IN BASEMENTS OF A RADON-PRONE REGION AND EVALUATION OF FURTHER RADON TESTING INDICATORS

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Abstract

The primary objective of this study was to investigate the temporal variability between basement winter short-term (7 to 10 days) and basement annual radon measurements. Other objectives were to test the short-term measurement's diagnostic performance at two reference levels and to evaluate its ability to predict annual average basement radon concentrations. Electret ion chamber (short-term) and alpha track (annual) radon measurements were obtained by trained personnel in Iowa residences. Overall, the geometric mean of the short-term radon concentrations (199 Bq m^{-3}) was slightly greater than the geometric mean of the annual radon concentrations (181 Bq m^{-3}). Short-term tests incorrectly predicted that the basement annual radon concentrations would be below 148 Bq m^{-3} 12% of the time and 2% of the time at 74 Bq m^{-3}. The short-term and annual radon concentrations were strongly correlated (r=0.87, p<0.0001). The foundation wall material of the basement was the only significant factor to have an impact on the absolute difference between the short-term and annual measurements. The findings from this study provide evidence of a substantially lower likelihood of obtaining a false negative result from a single short-term test in a region with high indoor radon potential when the reference level is lowered to 74 Bq m^{-3}.

Keywords

radon; detector; alpha-track; electrets; sampling

INTRODUCTION

The measurement of radon (^{222}Rn) is frequently obtained using short-term measurements in the lowest livable level of the home under "closed house" conditions when windows and

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outside doors are kept closed as much as possible (U.S. EPA 2009). The short-term measurement period typically ranges from two to 90 days depending on detector type. However, in the United States, the testing period usually lasts for two to five days because of the need for rapid testing during real estate transactions.

Long-term radon measurements, on the other hand, are collected under the ventilation conditions generally used by the occupant of the home (U.S. EPA 1992). Long-term testing lasts more than 90 days with an optimal measurement period of one year. Long-term measurements in frequently occupied rooms are preferable for assessing an individual's yearly radon exposure, as compared to short-term radon monitoring, because the longer measurement period helps to account for changes in meteorological conditions and occupant behavior (e.g., window opening, air conditioner usage). Long-term testing allows radon concentrations to be averaged over months or seasons rather than days or weeks generating more accurate estimates for radon exposure assessments.

Short-term measurements, obtained under "closed house" conditions, are considered screening tests as they provide an indicator of the potential for a home to have elevated radon concentrations. "Closed house" testing conditions are recommended by the U.S. Environmental Protection Agency (EPA) so that the measured radon concentrations will in most cases represent a worst-case scenario (i.e., maximizing the conditions for higher radon concentrations in a home) and as a result, would often times be larger than the long-term measurements (U.S. EPA 1992).

Lung cancer is the most established adverse health outcome associated with protracted exposure to radon and its decay products. A long-term radon measurement, therefore, would be more reflective of an individual's long-term exposure versus a short-term test. However, the EPA recommends that if a short-term radon test result performed under closed house conditions is above the radon action level of 148 Bq m^{-3}, this test can be followed by a second short-term test to make radon mitigation decisions (U.S. EPA 2009), but no further measurements are recommended if it is below the action level Because of both the widespread use of short-term tests to assess exposure to radon and the test measurements' influence on guiding individuals to take further action as needed, it is important to determine how well these measurements approximate long-term radon measurements as well as to evaluate their ability to predict long-term measurements. This comparison is needed to evaluate the correctness of decisions concerning the need for further radon testing to determine if installation of radon mitigation system is warranted.

Indoor radon concentrations can exhibit significant temporal variability (Klotz et al. 1993 Steck 1990 Ruano-Ravina et al. 2008 Wysocka et al. 2004) and are affected by housing factors (e.g., forced air heating system) and occupant practices (e.g., air conditioner usage) (Field et al. 1993). A specific aim of this study was to determine the temporal agreement between short-term and annual radon airborne measurements that were both collected at the same location in the lowest livable level of homes in the state of Iowa. This state is well-suited to this kind of study, as EPA surveys have found that Iowa has both the highest mean residential radon concentrations (241 Bq m^{-3}) and the greatest percentage (71%) of screening radon measurements above the EPA's action level of 148 Bq m^{-3} compared to any other state surveyed in the U.S. (White et al. 1992). According to the U.S. Geological Survey (2012), the high radon emanating potential of the glacial deposits that were deposited in Iowa are responsible for the state's elevated radon potential.

Other study aims were to evaluate the ability of the short-term radon measurement to predict the annual average radon measurement in the lowest livable level as well as to assess the effect of certain housing factors and occupant practices on the short-term and annual measurements. Few studies have examined the impact of these factors on the agreement between short-term and annual radon measurements. The agreement between short- and long-term annual radon measurements and the effect of housing and occupant factors on these measurements as well as their differences is an essential consideration in developing policies and communication materials on radon measurement testing and mitigation decision making.

MATERIALS AND METHODS

This study used existing data from the Iowa Radon Lung Cancer Study (IRLCS). The IRLCS, conducted from 1992 through 1997, was a population-based, case-control study that evaluated the association between protracted exposure to radon and its decay products and lung cancer among women in Iowa (Field et al 2000). Data collection for the survey questionnaire and radon measurements (placement, retrieval, quality assurance, and analyses) were done by trained personnel.

Sample selection

The criteria for inclusion in the IRLCS limited enrollment to female residents of Iowa between the ages of 40 and 84 years. Further requirements included residence in the current home for at least 20 consecutive years and no reports of modifications to one's home based on any previous radon testing. The final IRCLS data set included radon measurements from 413 homes with lung cancer cases and 614 homes with controls (a total of 1027 households).

Survey questionnaire

The study's questionnaire about the home collected information about rural versus urban residence, drinking water source(s), levels of the home, heating and cooling systems, ventilation, circulation, and weatherization. Another study questionnaire collected health-related information about active and passive tobacco exposure, personal and family health history, vitamin usage, and diet and cooking practices.

Radon measurements

Yearlong radon measurements were collected using alpha track detectors (ATD). At least one Radtrak ATD (Landauer, Inc., Glenwood, Illinois) was placed on each level of the home, in current and historic bedrooms, and in work area(s) within the home (e.g., office). The Radtrak ATD was selected based on its past record of good accuracy and precision over a multi-year period when compared to other commercially available ATDs (Pearson et al. 1992) as well as its low cost, mailability, and ease of use. Field assistants placed and retrieved the detectors after the one-year placement period. After retrieval, the ATDs were stored in a low radon environment (less than 7.4 Bq m^{-3}) prior to their return to Landauer, Inc. for processing.

In a subset of the homes, short-term measurements were made during the winter months by an E-PERM (Electret-Passive Environmental Radon Monitor) (Rad Elec, Inc., Frederick, Maryland) positioned approximately seven inches away from the ATD. These detectors were exposed for 7 to 10 days in the lowest livable area. E-PERMs were selected as the detector of choice to obtain the short-term measurements based on excellent accuracy and precision in a comparison of commercially available short-term radon detectors (Sun et al. 2006). Background gamma measurements were collected at the E-PERM placement site using a Ludlum Measurements, Inc. (Sweetwater, Texas) Model 19 micro-R survey meter. The lowest floor of the house was considered livable if the participant spent an average of at least 15 minutes per day on that level.

Houses with an initial site visit during November, January, or February when “closed house” conditions were more likely to be maintained were eligible for a short-term measurement. These were preferred months, primarily because of the potential of warmer weather outdoors and the potential for window opening in other months, increasing the possibility of failure to assure “closed house” conditions. Participants who completed short-term and annual measurements of radon were eligible for this study. The radon survey resulted in 189 lowest livable winter short-term and 930 lowest livable annual radon measurements. Alpha track and E-PERM measurements followed a quality assurance plan that is described elsewhere (Field et al. 1998).

Geocoding of home addresses

Zip codes of the homes were geocoded using ArcMap 8.3 (ESRI, Inc., Redlands, CA) and a 2009 TIGER/line file of Iowa as the reference address locator.

Data analysis

Descriptive statistics (e.g., geometric mean, geometric standard deviation) were computed for each type of radon measurement as well as their differences. Short-term and annual measurements were paired based on the site identification number where they were placed. The distribution of each measurement and their differences were evaluated using the Shapiro-Wilks’ test to assess normality and a Student’s paired t-test was performed to evaluate whether significant differences existed between both measurements. In the cases when the data did not follow a normal distribution, the data were transformed using a natural ln (log base e) followed by additional testing for normality.

The ability of the short-term measurement to classify the annual measurement (considered the “gold standard” for this comparison), with respect to being below or equal to or above the EPA’s radon action level of 148 Bq m^{-3} (Table 1), was used as an indication to make an informed decision for the need of additional radon testing. This classification procedure was repeated using a lower reference radon level of 74 Bq m^{-3} in order to compare the results to similar work performed by other investigators (Klotz et al. 1993). Findings at a reference level of 74 Bq m^{-3} are of interest since the EPA states that radon levels below 148 Bq m^{-3} also carries some risk for cancer and in most cases, radon concentrations can be reduced to

74 Bq m^{-3} or below (U.S. EPA 1992 Steck 2012). A lower artificially set reference level of 111 Bq m^{-3} was also examined to evaluate how the short-term tests categorically classified its annual measurement at a radon concentration similar to the World Health Organization's radon reference value of 100 Bq m^{-3} (World Health Organization 2009).

The classification rates at these reference levels that were examined were:

1. the probability of <u>correct classification</u> = number of occurrences when the short-term and annual measurements were both < reference level or both ≥ reference level;
2. the probability of obtaining a <u>true positive</u> (sensitivity) = P (short-term test ≥ reference level | annual test ≥ reference level);
3. the probability of the <u>positive predictive value</u> = P (annual test ≥ reference level | short-term test ≥ reference level); and
4. the probability of a obtaining a <u>false negative</u> (1 −sensitivity) = P (short-term test < reference level | annual test ≥ reference level).

In making these comparisons, the false negative rates are especially important as they are a measure of how often the short-term test incorrectly indicates that further radon testing is unnecessary, based on an annual measurement.

In addition to the agreement of the short-term radon test to classify the annual radon test by a reference level cutoff, it is helpful to know the usefulness of short-term radon tests for estimating long-term radon test results. The short-term radon test values were examined to determine whether they always represented the worst case radon scenario (i.e., maximized potential for a home to exhibit high radon concentrations). This type of interpretation is critical for providing evidence for the confidence of short-term radon measurements that can be incorporated in public information materials on radon measurement testing and mitigation decision making. To evaluate whether the radon concentration measured using an untransformed short-term test always yielded a worst case scenario, a 95% level of confidence or more with respect to the action level of 148 Bq m^{-3} was calculated. The "conclusive negative" short-term measurement value (i.e., lower limit of uncertainty range) was determined when 5% of the short-term tests were less than a short-term measurement value with untransformed annual tests equal to or greater than 148 Bq m^{-3}:

i. P (annual test ≥ 148 | short-term test < "conclusive negative" value) = 0.05

To illustrate this further, if the short-term test result was 80 Bq m^{-3} and the "conclusive negative" value was 100 Bq m^{-3}, for instance, the individual would be more than 95% confident that the annual test was less than 148 Bq m^{-3}.

The "conclusive positive" untransformed short-term measurement value (i.e., upper limit of uncertainty range) was determined when 5% of the short-term tests were greater than a short-term measurement value with untransformed annual tests less than the action level:

ii. P(annual test < 148 | short-term test > "conclusive positive" value) = 0.05

If the short-term test result was 250 Bq m^{-3} and the "conclusive positive" value was 200 Bq m^{-3}, for instance, the individual would be more than 95% confident that the annual test was equal to or larger than 148 Bq m^{-3}. If the short-term test result was between the "conclusive negative" and "conclusive positive" values, there would be less than 95% confidence that the annual test was less than 148 Bq m^{-3}. This type of interpretation is especially important if an individual obtains a short-term test value close to the action level. This clarification would inform the individual how certain one can be that the annual test will also be below the action level.

The ability of the short-term radon measurement to predict the annual radon measurement (i.e., predictor performance) using simple linear regression was also evaluated. Pearson's correlation coefficients were computed to determine the strength of the linear relationship between the short-term and annual radon measurements. To examine whether the errors (i.e., residuals) from this model were normally distributed, the Shapiro-Wilks' test was performed. If the errors did not follow a standard normal distribution, the measurements were ln-transformed.

Multiple regression models were also examined. These included: 1) the prediction of the annual radon measurements given certain housing factors and occupant practices; 2) the prediction of the short-term radon measurements given certain housing factors and occupant practices; and 3) the prediction of the absolute difference between the short-term and annual radon measurements given certain housing factors and occupant practices. Regression with absolute differences was selected to model the overall predictive performance of the difference (expected bias and variance) as a function of these factors since we were primarily interested in modeling mean absolute error as a function of housing and occupant factors rather than solely modeling average bias (i.e., signed difference).

Based on previous studies, important predictors of temporal radon variability have included type of heating system, presence of crawl space, fireplace usage, foundation wall construction material, presence of toilet, shower, washing machine or hot tub in the basement, presence of a sump pump, and proportion of first level below ground (Zhang et al. 2007). The case and control status of the study participants was also evaluated to assess whether radon measurements varied between cases and controls. Occupant behavior that affected radon concentrations (e.g., window opening, time spent in home) in the case population may have been modified once a diagnosis of cancer was made. A backward variable selection process was used to generate final regression models with predictor variables being retained given *p*-values less than 0.20 (Zhang et al. 2007). Analyses were performed using SAS version 9.2 (SAS Institute, Inc., Cary, North Carolina).

RESULTS

All lowest livable level measurements in this study were obtained in the basement. Seven hundred seventy two annual basement and 18 winter short-term radon measurements were excluded due to a lack of a corresponding winter short-term basement and annual basement measurement, respectively. This resulted in the inclusion of 158 basement short-term tests and 158 respective basement annual measurements for this study.

Sample characteristics

The mean duration of the basement winter short-term radon measurements was 8.4 days (SD=2.7) and ranged from three to 27 days with a median of 7.5 days. Thirty-six (23%) measurements were obtained in the month of January, 30 (19%) in February, 34 (21%) in March, 4 (2.5%) in April, 25 (16%) in November, and 29 (18%) in December. The average background gamma exposure rate of the area where a detector was deployed was 9.7 microroentgens (μR) per hour and ranged from 3 to 17 μR per hour.

Fig. 1 displays the approximate location of the study participants and their relative basement winter short-term and corresponding basement annual radon measurements. Graduated symbols distinguish areas with regard to the EPA's radon action level of 148 Bq m^{-3}. Paired radon measurements were collected in homes located in 65 of the 99 counties in Iowa.

After both measurements were ln-transformed, the Shapiro-Wilks' test supported normality of the distributions for the basement winter short-term (p=0.14) and basement annual (p=0.27) measurements. The basement winter short-term radon concentrations ranged from 42 to 1,331 Bq m^{-3}, with a geometric mean of 199 Bq m^{-3} (GSD=2.0) (Table 2). The basement annual concentrations had a slightly lower geometric mean of 181 Bq m^{-3} (GSD=2.0). About 63% of the short-term tests and a slightly lower percentage (60%) of the annual tests were equal to or above the EPA's radon action level of 148 Bq m^{-3}. The absolute difference between the basement short-term and annual radon concentrations ranged from 0.39 to 738 Bq m^{-3}. There was a larger percentage (61%) of the short-term radon measurements greater than their matching annual measurements compared to annual measurements greater than their respective short-term measurements (39%) (not presented in Table 2).

Agreement between measurements

The ability of the untransformed short-term radon measurement to classify the categorical untransformed annual radon concentration by the specified reference level is presented in Table 3. The correct classification rate of the number of occurrences for which the short-term radon test matched its corresponding annual radon test category, as both larger than or equal to or less than the action level of 148 Bq m^{-3} was 83%. This rate increased to 92% when the reference level was lowered to 74 Bq m^{-3}. Among the short-term measurements between 111 and 148 Bq m^{-3}, about 40% (N = 11) had annual measurements equal to or above 148 Bq m^{-3}. Fifty percent had annual measurements equal to or above 148 Bq m^{-3} when the short-term measurements were between 55.5 and 74 Bq m^{-3} (N = 4) at a 74 Bq m^{-3} reference level.

Given the annual radon concentration was equal to or larger than the action level of 148 Bq m^{-3}, the probability of the short-term radon concentration also being equal to or larger than this level (i.e., sensitivity) was 88% (95% CI: 80, 94) and increased to 98% (95% CI: 94, 100) when the reference level was reduced to 74 Bq m^{-3} (Fig. 2). The probability of an annual test being equal to or larger than the action level of 148 Bq m^{-3} given the short-term test was also equal to or larger than this level (i.e., positive predictive value) was 84% (95% CI: 75, 91). The positive predictive value estimate increased slightly to 86% (95% CI: 79,

91) for a lower reference level of 111 Bq m^{-3}, but its confidence interval overlapped with the interval at the previous reference level. This value estimate increased further to 94% (95% CI: 89, 97) when it was lowered to a 74 Bq m^{-3} reference level (its confidence interval also overlapped for estimates with intervals at higher reference levels). The probability of the short-term test being less than 148 Bq m^{-3} when the annual measurement was equal to or larger than 148 Bq m^{-3} (i.e., false negative rate) was about 12% (95% CI: 6, 20). At lower reference levels of 111 and 74 Bq m^{-3}, the false negative rate estimates dropped considerably to 4 (95% CI: 1, 10) and 2% (95% CI: 0, 6), respectively.

In the assessment of the winter short-term tests for decision making about the need of further radon testing with respect to the action level of 148 Bq m^{-3}, the "conclusive negative" short-term measurement value (i.e., lower limit of uncertainty range) was 122 Bq m^{-3} and the "conclusive positive" (i.e., upper limit of uncertainty range) was 214 Bq m^{-3}. If the short-term test value was less than 122 Bq m^{-3}, the individual would be more than 95% confident that the annual test was less than 148 Bq m^{-3}. If a short-term test value was larger than 214 Bq m^{-3}, the individual would be more than 95% confident that the annual test was equal to or above 148 Bq m^{-3}. If the short-term test was between 122 Bq m^{-3} and 214 Bq m^{-3}, the individual would be less than 95% confident that the annual test was less than 148 Bq m^{-3}.

Simple linear regression

A strong linear relationship was noted (Pearson's correlation coefficient *(r)* = 0.87, $p < 0.0001$) between ln-transformed basement winter short-term radon concentrations and ln-transformed annual radon concentrations (Fig. 3). The *r*-squared value indicated that 75% of the variability in the basement annual radon measurements can be explained by the basement winter short-term radon measurements.

Backward stepwise regression

The radon concentrations in the three models were ln-transformed. The housing and occupant factors that were selected for the regression models can be found in Table 4.

The variance inflation factors (VIF) for each variable in the three final regression models were close to one, indicating that the predictor variables were not strongly correlated (i.e., multicollinearity). Table 5 lists the variables that remained in the multiple regression model for annual radon concentration. The factors that were positively associated with the annual radon concentrations were the presence of central air conditioning and presence of a sump in the basement and negatively associated were having a poured concrete basement foundation wall and a clothes dryer in a basement. The final model's *R*-squared value indicated that 16% of the variability in the basement annual radon concentrations can be explained by all these factors.

With all the other variables fixed in the model, the basement annual radon concentration was: 24% smaller, i.e., $(e^{-0.28} - 1.0) \times 100$, in homes with a poured concrete versus a concrete block foundation wall; 65% larger, i.e., $(e^{0.50} - 1.0) \times 100$, in homes with central air conditioning versus homes without central air conditioning; 20% smaller in homes with a clothes dryer in the basement compared to those without one; and 45% larger in homes with a sump in the basement versus homes without a sump.

Variables that remained in the regression model for predicting basement winter short-term radon concentrations can be found in Table 6. The factors that were positively associated with basement winter short-term radon concentrations were the presence of central air conditioning and presence of a sump in the basement. The factor that was negatively associated with basement winter short-term radon concentrations was the presence of a clothes dryer in the basement. The final model's R-squared value showed that 17% of the variability in the basement winter short-term radon concentrations can be explained by all these factors.

With all the other variables adjusted for in the model, the basement short-term concentration was 62% larger in homes with central conditioning versus homes without central air conditioning, 32% smaller in homes with a clothes dryer in the basement compared to those without one, and 63% larger in homes with a sump in the basement versus homes without a sump.

The only variable that remained in the regression model for predicting the absolute paired difference was the foundation wall material in the basement (p=0.08) (Table 7). The final model's R-squared value showed that only 3% of the variability in the absolute paired differences can be explained by the foundation wall material. The difference between the basement winter short-term and the basement annual radon concentration decreased by 38% in homes with a poured concrete versus a concrete block foundation wall.

Quality assurance

Detailed information about the quality control for the alpha track detectors is presented elsewhere (Field et al. 1998). E-PERMS underwent annual periodic testing for accuracy in the EPA's radon test chamber. The relative error of the measurements was within 15% for one week equivalent radon concentrations of 74 Bq m^{-3}, 148 Bq m^{-3}, and 222 Bq m^{-3}. The COVs were all less than 10% for all three exposure levels. Ten percent of placements had collocated detectors to assess detector precision. The COVs for the duplicate placements were all less than 10%. Ten percent of the E-PERMs were field controls (i.e., blanks) and no extraneous radon exposure was detected.

DISCUSSION

Among the 158 residences tested for radon in this study, the geometric mean of the basement winter short-term radon concentrations was 199 Bq m^{-3} (GSD=2.0). In comparison, a larger geometric mean (241 Bq m^{-3}, GSD=2.5) was found in the EPA state radon survey for Iowa (White et al. 1992) for two-day screening radon concentrations obtained during the winter, examining 1,208 residences with basements. More than half (63%) of the basement winter short-term radon concentrations were at or above the EPA's action level of 148 Bq m^{-3}. In contrast, the EPA state radon survey for Iowa found a larger percentage (71%) of screening radon measurements above this guidance level.

The basement weeklong winter short-term radon concentrations were significantly different from their respective basement annual radon concentrations. The geometric mean of the basement short-term concentrations overestimated the geometric mean of the basement annual concentrations (181 Bq m^{-3}, GSD=2.0) by 18 Bq m^{-3}. A similar trend was observed in a survey of more than 300 residences in Poland by Wysocka et al. (2004) and in a study of 709 New Jersey homes by Klotz and colleagues (1993) where the average of four-day winter basement radon measurements also overestimated their corresponding annual average basement radon concentrations by 34 and 8 Bq m^{-3}, respectively.

A single weeklong basement short-term measurement to classify correctly its corresponding basement annual measurement as below or equal to or above the EPA's action level of 148 Bq m^{-3} was 83%. This rate improved considerably to 92% at a lower, artificially set reference level of 74 Bq m^{-3}. A general trend of increasing sensitivity and positive predictive value rates was noted with decreasing reference radon concentrations with statistically significant differences identified for the high (148 Bq m^{-3}) and low (74 Bq m^{-3}) reference radon concentrations.

In making these comparisons, the false negative rates are especially important as they are a measure of how often the short-term test incorrectly indicates that further radon testing is unnecessary, based on an annual measurement. The short-term measurements in this study differ from the "usual screening measurement(s)" which is often a single, very short-term (i.e., two-day) placement in any season of side-by-side charcoal canister detectors. Consequently, these typical short-term measurements, obtained during conditions when windows and doors are either open or closed, may result in larger false negative rates. In this study, the false negative rate was high (12%, 95% CI: 6, 20) at the action level of 148 Bq m^{-3}, but dropped considerably (2%, 95% CI: 0, 6) at a lower reference level of 74 Bq m^{-3}.

Based on estimates made by the National Research Council's BEIR VI Committee (1999), about one-third of cancers attributable to radon could be prevented by lowering radon concentrations below the action level of 148 Bq m^{-3} nationwide. To reduce radon-related lung cancer deaths in the U.S. by half, the Committee further estimated that radon concentrations in all homes in the U.S. could not exceed 74 Bq m^{-3}. Decisions made based on these short-term test results at the current action level would incorrectly indicate to individuals taking these tests that further radon testing is not needed 12% of the time and therefore likely contribute to poor decision making and no action to continue to evaluate the radon potential in one's home. The findings from this study provide evidence of a substantially lower likelihood of obtaining a false negative result from a single short-term test in a region with high indoor radon potential (U.S. EPA 2012) when the reference level is set at 74 Bq m^{-3}. There may be less certainty of obtaining an annual measurement below 148 Bq m^{-3} when the short-term measurement is near 148 Bq m^{-3}. In this study, the likelihood of an annual measurement being equal to or above the action level when the short-term measurement was between 111 and 148 Bq m^{-3} was 40%. The findings indicate that if a short-term test value is below 122 Bq m^{-3}, the individual taking the test would be more than 95% confident that the annual test was less than 148 Bq m^{-3}. If the short-term test value was between 122 and 214 Bq m^{-3}, however, the individual would be less than 95% confident that the annual test was less than 148 Bq m^{-3} and additional radon testing would be advised. This conclusive short-term test value should not been interpreted as representative or transferable for testing that occurs in other seasons, in other locations within a residence, and for longer-term tests.

The common significant housing factors that were suggestive of influencing the basement winter short-term and the basement annual radon concentrations were the presence of central airconditioning, the presence of a clothes dryer in the basement, and the presence of a sump in the basement. The foundation wall material of the basement was the only significant factor to have an impact on the absolute difference between both measurements and a significant factor for influencing the basement annual radon concentrations. The paired differences between the short-term and annual measurements were smaller in homes with a poured concrete foundation wall in the basement compared to homes with a concrete block foundation wall.

An earlier study in Iowa by Field et al. (1993) examined the effect of housing factors on screening measurements in 582 households. Field and colleagues found houses with higher radon screening concentrations to be positively and significantly associated with a crawl space in the basement and presence of a non-poured concrete wall in unfinished basements, which were not significantly associated with short-term measurements in this study. Having a crawl space was only significantly associated with larger radon concentrations when the placement of the radon detector was considered. Homes with crawl spaces were significantly associated with larger radon concentrations in unfinished basements compared to homes without a crawl space and in main floor rooms compared to homes without a crawl space (p=0.004 and p=0.0003, respectively).

The significant factors affecting annual average radon concentrations as part of follow-up testing for the Iowa Radon Lung Cancer Study (Field et al. 2000) when accounting for type of house and floor where the radon measurements took place, included an unfinished basement; lack of an insulated ceiling; presence of a crawl space; year of home construction; location of lowest home level relative to the ground; and presence of a toilet, bathtub, shower, washing machine, or hot tub in the basement. This study, however, did not find the number of major plumbing penetrations in the basement (e.g., toilet, washing machine) to be significantly associated with annual radon concentrations.

Limitations

A limitation of the study is the lack of climate-related data to assess the influence of climate conditions on local geological conditions (e.g., soil porosity) and therefore, its effect on the variability in the agreement between winter short-term and annual radon concentrations. It should be noted, however, that the findings from this study are most generalizable to residences in the Midwestern region of the United States with high average screening radon concentrations where similar climate patterns and construction practices are found.

Strengths

This study explores the relationship between radon short-term and year-long measurements in the lowest livable level in a robust data set of measurements that included a stringent quality assurance/quality control plan. It was carried out in a manner to minimize the potential of measurement errors by a number of approaches. The first approach was to test residences for radon in the winter months in the Midwestern region of the U.S. when “closed house” conditions are generally maintained. The possibility of failure to assure “closed house” conditions during the other months, primarily because of the potential for warmer weather outdoors and the potential for window opening, precluded placement of short-term measurements during non-heating seasonal months.

Previous studies that compared short-term radon measurements to long-term measurements on the same floor did not incorporate methods that maximized the reliability (e.g., accuracy, precision) of the short-term radon test (Ruano-Ravina et al. 2008 Wysocka et al. 2004 Klotz et al. 1993). For example, the E-PERMs used in this study are not affected by humidity (Rad Elec, Inc) and provide a true integrated mean radon measurement. In addition, the 7 to 10 day duration of the screening measurement period minimized the effect of fluctuations in radon concentrations due to weather-related events.

CONCLUSIONS

The data generated from this study provide insight into the ability of a single short-term radon test to appropriately match the predictions of a recommended long-term annual test with respect to being below or equal to or above the EPA’s radon action level of 148 Bq m^{-3} as well at a lower reference level. This study was performed in a state with the highest mean radon concentrations and the greatest percentage of screening radon measurements above the EPA’s action level of 148 Bq m^{-3} compared to any other state surveyed in the U.S. The findings from this study provide evidence of a substantially lower likelihood of a false negative test from a single short-term radon measurement in a region with high indoor radon potential when the reference level is lowered to 74 Bq m^{-3} from 148 Bq m^{-3}.

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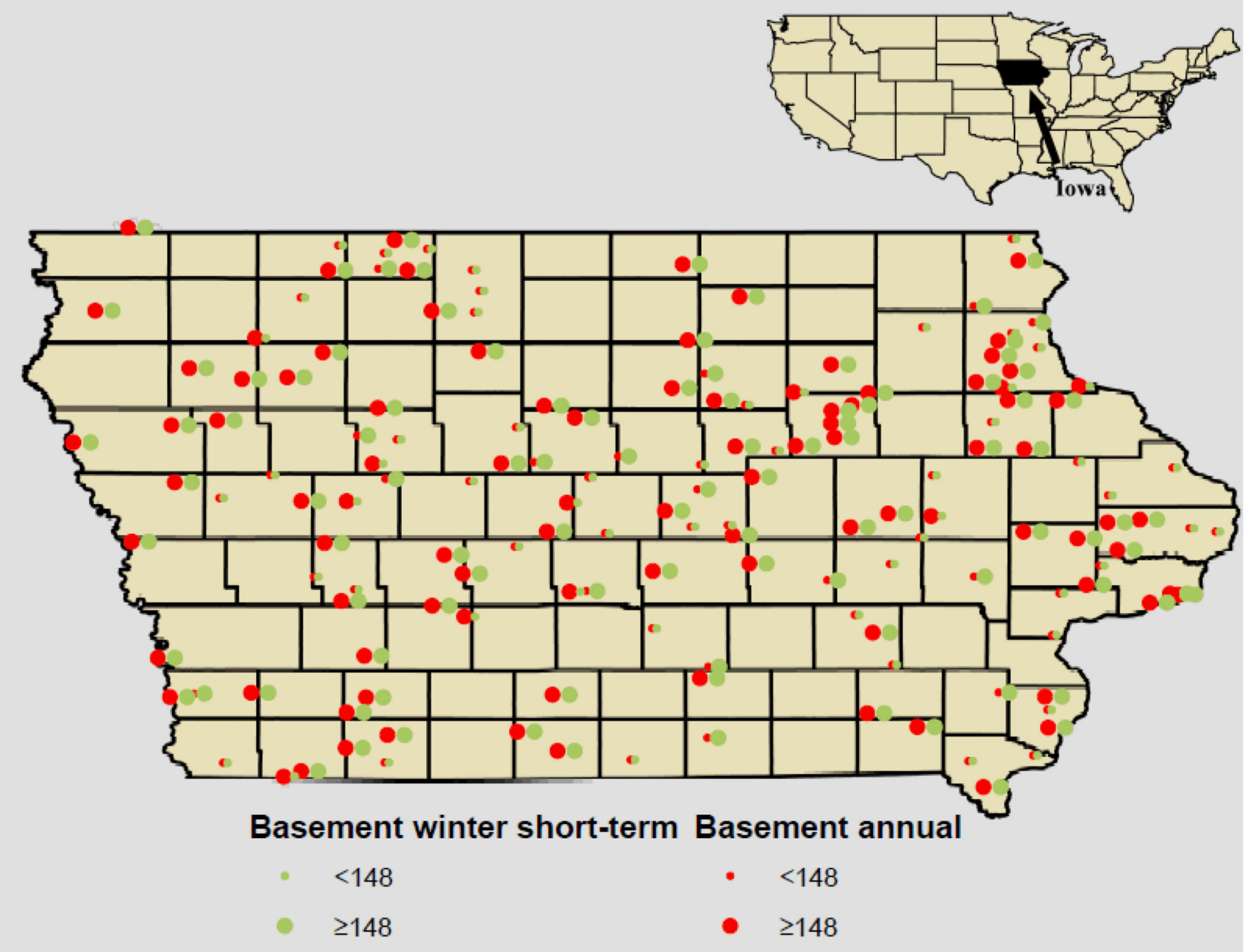

Fig. 1.

Map of basement winter short-term and basement annual radon concentrations with respect to EPA's action level of 148 Bq m^{-3} in Iowa

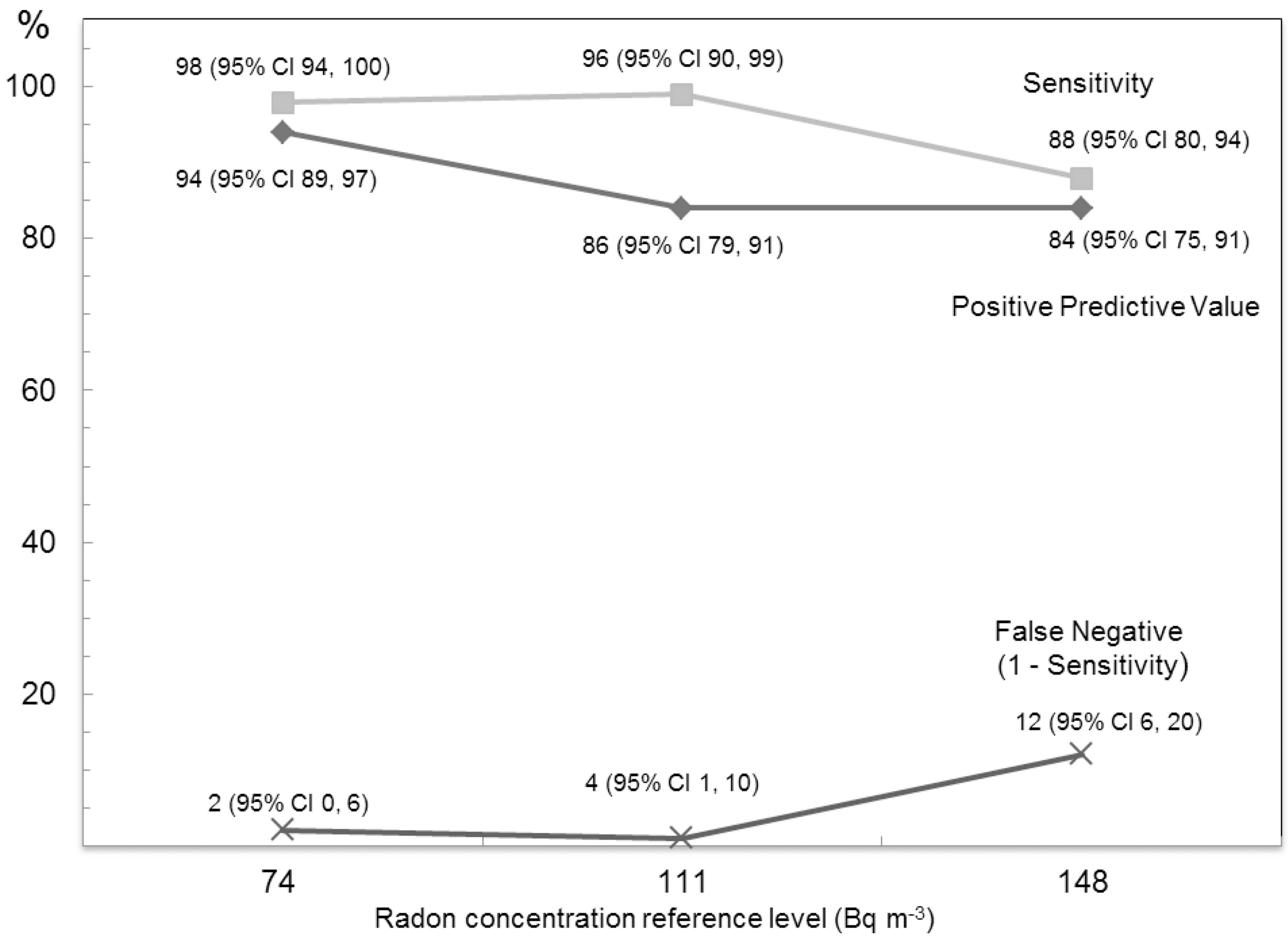

Fig. 2.

Percentages of diagnostic indicators comparing basement short-term radon tests to basement annual radon tests by reference level

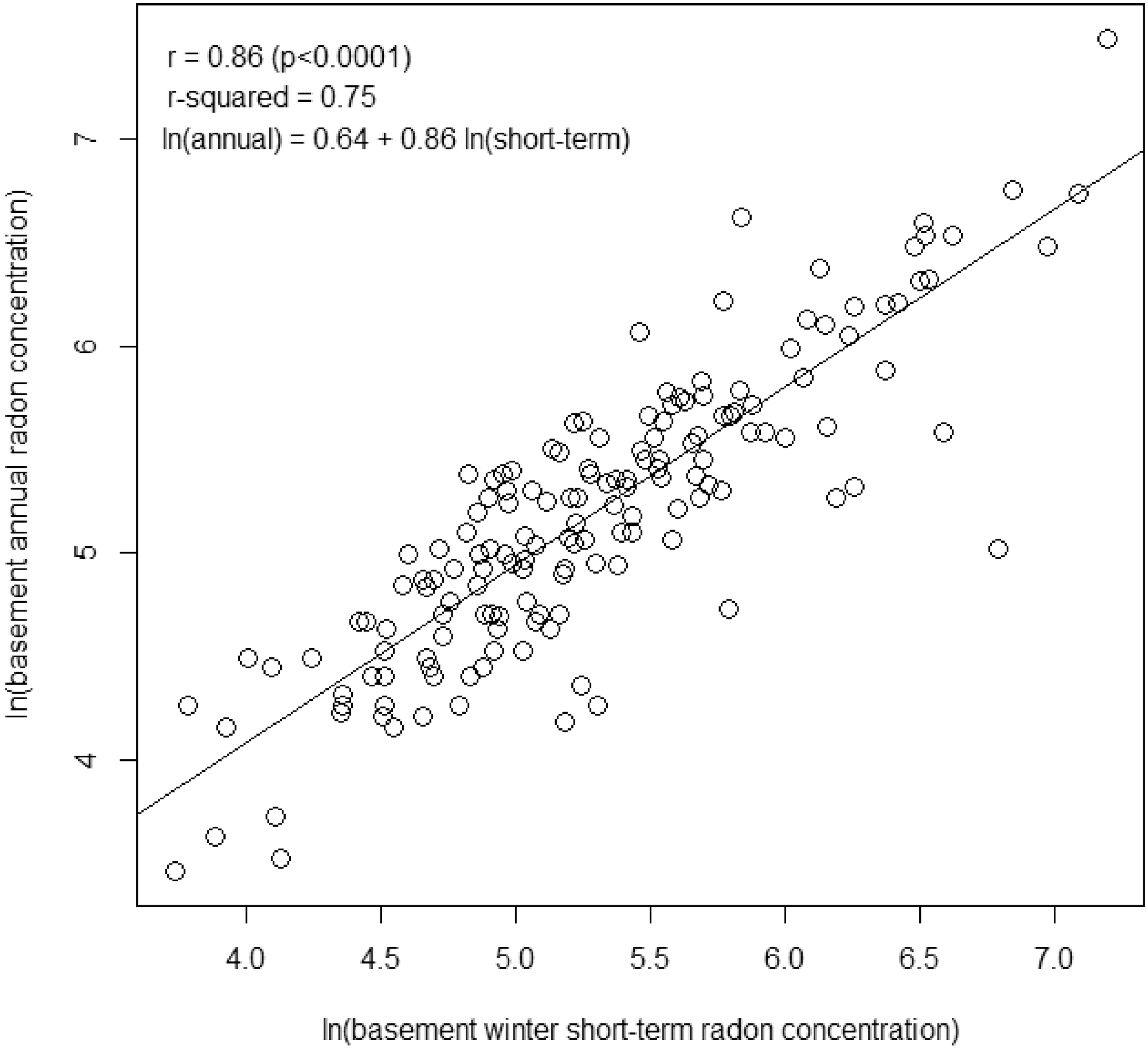

Fig. 3.

Scatter plot of ln(basement winter short-term radon conc.) versus ln(basement annual radon conc.)

Table 1

Interpretation of short-term and annual radon measurements that were equal to or above or less than the respective reference level

	Basement annual alpha track measurement (Bq m^{-3})			
Basement winter short-term electret ion chamber measurement (Bq m^{-3})	**≥ 74**	**< 74**	**≥ 148**	**< 148**
≥ 74	True Positive[a]	False Positive[b]	-	-
55.5 < ST test < 74	False Negative[c]	True Negative[d]	-	-
≤ 55.5	False Negative	True Negative	-	-
≥ 148	-	-	True Positive	False Positive
111 < ST test < 148	-	-	False Negative	True Negative
≤ 111	-	-	False Negative	True Negative

[a] True Positive - short-term test correctly indicates that further radon testing is necessary.

[b] False Positive - short-term test incorrectly indicates that further radon testing is necessary.

[c] False Negative – short-term test incorrectly indicates that further radon testing is not necessary.

[d] True Negative - short-term test correctly indicates that further radon testing is not necessary.

Table 2

Characteristics of basement winter short-term and basement annual radon measurements (Bq m^{-3}) as well as their differences from 158 residences in Iowa

Characteristic	Basement Winter Short-Term Electret Ion Chamber Test	Basement Annual Alpha Track Test	Difference | Short-Term - Annual |
Geometric Mean (GSD)	199 (2.0)	181 (2.0)	34 (3.6)
Range	42 – 1331	32 – 1787	0.39 – 738
25th Percentile	129	110	19
Median	185	186	38
75th Percentile	297	266	74
≥ 148 Bq m^{-3}	63%	60%	

Table 3

Number of basement short-term and basement annual radon measurements that were equal to or above or less than the respective reference level

	Basement annual alpha track measurement (Bq m^{-3})			
Basement winter short-term electret ion chamber measurement (Bq m^{-3})	**≥ 74**	**< 74**	**≥ 148**	**< 148**
≥ 74	140	9	-	-
55.5 < ST test < 74	2	2	-	-
≤ 55.5	1	4	-	-
≥ 148	-	-	84	16
111 < ST test < 148	-	-	11	17
≤ 111	-	-	0	30

Table 4

Summary of regression predictor parameters from 158 homes in Iowa

Characteristic	N (%)	Mean (SD), Median
Basement foundation wall material		-
Concrete block	82 (51.9)	
Poured concrete	45 (28.5)	
Neither concrete block nor poured concrete	31 (19.6)	
Case/control status of participants		-
Case	48 (30.4)	
Control	110 (69.6)	
Number of major plumbing penetrations in basement	123 (77.8)	2.0 (0.9), 2.0
Missing	35 (22.2)	
Percentage of basement underground	150 (94.9)	82 (18), 90
Missing	8 (5.1)	
Presence of central air conditioning		-
Yes	112 (70.9)	
No	46 (29.1)	
Presence of clothes dryer in basement		-
Yes	96 (60.8)	
No	62 (39.2)	
Presence of crawl space in basement		-
Yes	72 (45.6)	
No	86 (54.4)	
Presence of forced air heating system		-
Yes	130 (82.3)	
No	28 (17.7)	
Presence of sump in basement		-
Yes	33 (20.9)	
No	122 (77.2)	
Missing	3 (1.9)	
Volume of basement	158 (100)	5779 (2826), 5618

Table 5

Regression parameters (final model) for predicting ln(basement *annual* radon concentration)

Predictor	**β coeff.**[a] **(SE**[b]**)**	**Student's t-test (*p*)**	**Percent change**[c]
Basement foundation wall material			
Concrete block	Ref.[d]	-	
Poured concrete	−0.28 (0.15)	−1.9 (0.06)	24
Presence of central air conditioning			
Yes	0.50 (0.17)	3.0 (0.004)	65
No	Ref.	-	
Presence of clothes dryer in basement			
Yes	−0.22 (0.16)	−1.4 (0.17)	20
No	Ref.	-	
Presence of sump in basement			
Yes	0.37 (0.16)	2.3 (0.02)	45
No	Ref.	-	
R^2	0.16		
Adjusted R^2	0.12		

[a] Slope parameter estimate.

[b] Standard error.

[c] Given all other variables were fixed in model.

[d] Reference category

Table 6

Regression parameters (final model) for predicting ln(basement winter *short-term* radon concentration)

Predictor	**β coeff.**[a] **(SE**[b]**)**	**Student's t-test (*p*)**	**Percent change**[c]
Presence of central air conditioning			
Yes	0.48 (0.17)	2.9 (0.01)	62
No	Ref.[d]	-	
Presence of clothes dryer in basement			
Yes	−0.39 (0.16)	−2.5 (0.01)	32
No	Ref.	-	
Presence of sump in basement			
Yes	0.49 (0.16)	3.0 (0.003)	63
No	Ref.	-	
R^2		0.17	
Adjusted R^2		0.15	

[a] Slope parameter estimate.

[b] Standard error.

[c] Given all other variables were fixed in model.

[d] Reference category.

Table 7

Regression parameter (final model) for predicting the *absolute difference*, ln(| basement short-term radon conc. - basement annual radon conc |)

Predictor	**β coeff.**[a] **(SE**[b]**)**	**Student's t-test (*p*)**	**Percent change**[c]
Basement foundation wall material			
Concrete block	Ref.[d]	-	
Poured concrete	−0.48 (0.27)	−1.8 (0.08)	38
R^2		0.03	
Adjusted R^2		0.02	

[a] Slope parameter estimate.

[b] Standard error.

[c] Given all other variables were fixed in model.

[d] Reference category.