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UTILITY OF SHORT-TERM BASEMENT SCREENING RADON MEASUREMENTS TO PREDICT YEAR-LONG RESIDENTIAL RADON CONCENTRATIONS ON UPPER FLOORS

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This study investigated temporal and spatial variability between basement radon concentrations (measured for ∼7 d using electret ion chambers) and basement and upper floor radon concentrations (measured for 1 y using alpha track detectors) in 158 residences in Iowa, USA. Utility of short-term measurements to approximate a person's residential radon exposure and effect of housing/occupant factors on predictive ability were evaluated. About 60 % of basement short-term, 60 % of basement year-long and 30 % of upper floor year-long radon measurements were equal to or above the United States Environmental Protection Agency's radon action level of 148 Bq m^{-3}. Predictive value of a positive short-term test was 44 % given the year-long living space concentration was equal to or above this action level. Findings from this study indicate that cumulative radon-related exposure was more closely approximated by upper floor year-long measurements than short-term or year-long measurements in the basement.

INTRODUCTION

Exposure to indoor residential ^{222}Rn (hereafter referred to as radon) gas is generally estimated in the USA from short-term radon measurements made on the lowest liveable level of a home. The short-term measurement period typically ranges from 2 to 90 d. In the USA, the most common testing period usually lasts for 2–5 d because of the need for rapid results to complete real-estate transactions. Short-term radon tests, collected under 'closed house' conditions, are recommended initially by the United States Environmental Protection Agency (US EPA) to assess a home's potential to have radon concentrations equal to or exceeding the US EPA's action level of 148 Bq m^{-3}. In addition, a single measurement of this type, obtained in the basement where the occupancy time is often limited[(1)], is also used in some cases to approximate the radon concentrations in the upper floors of the home as a rough estimate of an individual's average radon exposure.

In contrast, long-term testing lasts more than 90 d[(2)] with an optimal measurement period of 1 y to account for seasonal radon variation. Long-term radon detectors are generally placed in the most frequently occupied living areas of the home, usually in a non-basement first floor[(2)] room, and provide a more accurate assessment of an individual's yearly residential radon exposure than short-term radon measurements. Investigators have reported that an individual's overall radon exposure was approximated more accurately by a first floor radon measurement rather than a radon measurement in the basement[(3, 4)]. Some housing factors that increased the variability of long-term radon measurements in a previous Iowa study included the presence of a crawl space, fireplace usage, foundation wall material, presence of a plumbing penetration (e.g. toilet, bathtub, shower, washing machine) in the basement and proportion of the first level below ground[(5)].

Estimates of radon exposure can also vary significantly with detector placement location on different levels (e.g. basement and first floor) within a residence[(6, 7)]. The variation of radon concentrations between floors can limit the ability of both a short- and long-term radon measurement taken in the basement to predict the long-term radon concentration on an upper floor of the home. Examining factors that can influence the degree of agreement between short- and long-term radon measurements is helpful in understanding the predictive ability (i.e. predictor performance) of a short-term test to characterise the distribution of longer-term measurements on the same or another level within a residence. Housing factors that have influenced substantially the agreement between year-long radon concentrations in Iowa homes between floor levels included the type of heating system and volume of the basement[(6)].

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Previously, the authors reported that the geometric mean (GM) of the basement winter short-term (BWS) radon concentrations (199 Bq m^{-3}) slightly overestimated the GM of basement annual average radon concentrations (181 Bq m^{-3}) in 158 residences included in the Iowa Radon Lung Cancer Study[8]. About 60 % of basement short-term and 60 % of basement year-long (BY) measurements were equal to or above the US EPA's radon action level of 148 Bq m^{-3}. The authors also reported that the common factors influencing both the basement short-term and annual radon concentrations were the presence of central air conditioning, the presence of a clothes dryer in the basement and the presence of a sump in the basement[8]. However, the findings indicated that the foundation wall material of the basement was the only factor that affected the difference between short-term and year-long measurements.

The primary aim of this study is to examine the ability of a BWS radon measurement to predict the annual radon concentration on the upper floors. Further aims of the study were to examine the utility of these radon measurements to approximate a person's radon exposure and to assess the effect of a priori selected housing factors and occupant practices on the measurement of radon over time and across floor levels.

MATERIALS AND METHODS

Sample selection

Radon measurement data for this study were obtained from the Iowa Radon Lung Cancer Study (IRLCS), which was funded by the National Institutes of Environmental Health Sciences and performed from 1993 to 1997[9]. The study's inclusion criteria included (1) being a resident of the state of Iowa for the previous 20 y prior to inclusion in the study, (2) female, (3) aged between 40 and 84 y, (4) residence in one's current home for at least the previous 20 consecutive years prior to inclusion in the study and (5) no reports of making modifications to one's home to reduce radon concentrations. There were 413 homes with lung cancer cases and 614 homes with controls (i.e. individuals without lung cancer) included in the IRLCS. Participants from the IRLCS who met all the inclusion criteria and completed BWS, BY and upper floor (i.e. non-basement) year-long measurements of radon were eligible for this study.

Questionnaire

Each study participant was mailed a questionnaire to collect information about heating, ventilation and air-conditioning patterns, smoking history and characteristics of the home. The IRLCS research staff conducted a home inspection and face-to-face interview to assure the completeness of the questionnaires.

Radon measurements

At least one Radtrak Alpha Track Detector (ATD) (Landauer, Inc., Glenwood, IL, USA), which was used to obtain a year-long radon measurement, was placed on each level of the home, in current and historical bedrooms and in work area(s), as applicable, within the home (e.g. home office). The location and number of rooms measured were selected based on where the participant spent the most time over the past 20 y. At least one Electret-Passive Environmental Radon Monitor (E-PERM) (Rad Elec, Inc., Frederick, MD, USA) was placed by study personnel in a subset of the homes during the winter months (i.e. to ensure 'closed house' conditions) to obtain a short-term radon measurement alongside the basement-level ATD.

The homes selected for this study were based on two factors: (1) the initial visit of the IRLCS personnel occurred during months when 'closed house' conditions could be assumed to have occurred (i.e. November, January or February)[8] and (2) the participant's willingness and/or ability to return the E-PERM to the laboratory after the short-term exposure period. The basement E-PERM detectors were left in the home for a median of 7.5 d (range: 3–27 d)[8]. All E-PERM measurement results were adjusted for background gamma radiation at the measurement location using a calibrated Ludlum Measurements, Inc. (Sweetwater, TX, USA) Model 19 μR meter. All radon measurements followed a quality assurance plan that has been described previously[8, 10].

Data distributions

Six different radon distributions are presented and discussed.

Direct radon measurement distributions described in the previous section:

- BWS
- BY

Distributions calculated from direct radon measurements:

- First floor year-long (FFY): mean of all non-basement first floor year-long measurements.
- Absolute paired difference between FFY and BWS (DFB).
- Annual living area average (ALAA): mean of bedroom and living room year-long measurements.
- Cumulative radon-related exposure (CRE): long-term radon-related exposure estimate calculated as described below.

Year-long radon measurements in homes, offices and outdoor locations that were collected during the IRLCS were used to compute a temporally and spatially linked radon-related exposure estimate for each participant[9] for each year during a retrospective 15-y

period. The assessment period, 5–19 y prior to participant enrolment, was selected because 4 y is considered the minimum latency period for lung cancer, and 20 y was the minimum duration of residency of participants in their current home, which eliminated the need to impute any radon measurement data[9].

Each annual exposure was estimated from the annual average radon concentrations in multiple locations in their home (e.g. bedroom, living area and basement) weighted by the per cent of time that the participants spent in these areas as well as outside the home (e.g. outdoors, inside other buildings and out of state on vacation) during that part of the year (Equation 1). The estimation of outdoor radon exposure and exposure inside other buildings is presented elsewhere[9]. Because the year-to-year residential radon variation was found to be low, typically <25 %, in study homes[5, 11], the use of radon measurements from the year-long measurement period provided a good approximation of the 15-y study period.

Cumulative radon-related exposure in working level months (WLMs) for year y was expressed as follows:

$$\mathrm{WLM} = \frac{\lambda}{170 \times 100} \sum_{l} h_{\mathrm{ly}}\, r_{l} \qquad (1)$$

where λ is assumed equilibrium factor of 50 %, h_{ly} represents total hours spent at location l during the yth year prior to enrolment and r_{l} represents radon concentration ($\mathrm{pCi\,l^{-1}}$) at location l.

The cumulative radon exposure was calculated in WLM since the retrospective period was also the critical period of exposure for lung cancer development in miner-based radon studies for which the WLM was applied as the exposure metric[9]. A working level (WL) is 'any combination of the short-lived progeny of radon in 1 l of air, under ambient temperature and pressure, that results in the ultimate emission of 1.3×10^5 MeV of alpha particle energy'[12]. One WL translates to 100 pCi $\mathrm{l^{-1}}$ (3700 Bq $\mathrm{m^{-3}}$) of radon's short-lived decay products in equilibrium[12]. A WLM is a cumulative exposure equivalent to one WL for a working month (170 h). Conversion of exposure from radon to exposure from short-lived decay products, referred to as radon-related exposure, uses the equilibrium factor to account for the losses of airborne decay products in a space due to surface deposition and air exchange.

The equilibrium factor is the ratio of the actual WL in the air available for inhalation to the maximum, which would be available if the radon and its decay products were in radioactive equilibrium[13]. Although the equilibrium factor varies with location and time, a constant equilibrium ratio of 50 % was used as it is generally applied by the US EPA based on studies conducted in the USA[13]. The CRE can be compared with the usual exposure metric used in most residential studies (i.e. radon concentration) by noting that 11 WLM is roughly equivalent to the exposure in an average residential concentration of 148 Bq $\mathrm{m^{-3}}$ (4 pCi $\mathrm{l^{-1}}$) for 15 y at a 70 % home occupancy[9, 12].

Descriptive analysis

Descriptive statistics were computed for the six data distributions after they were analysed for normality as described in detail elsewhere[8].

Diagnostic performance of radon distributions

Screening radon measurements, like the BWS measurements, are used to decide whether it is likely that radon concentrations in living areas exceed the US EPA's radon action level of 148 Bq $\mathrm{m^{-3}}$. The current US EPA protocol recommends additional radon testing when an initial screening test exceeds this action level. In time-sensitive circumstances, like real-estate transactions, either the initial screening test or the average of the initial test and an immediate follow-up test are commonly used to decide about the need for mitigation even though longer testing periods in living areas[13] are more fitting for decision-making.

Diagnostic statistics, such as the probability of a positive test result to occur in a house with living area radon equal to or above the action level, provide a measure of the reliability and potential for misclassification of radon exposure using screening tests. Although radon concentrations on upper floors are typically lower than those in the basement, protracted exposure to radon concentrations between 74 and 148 Bq $\mathrm{m^{-3}}$ also carries significant lung cancer risk[14–16]. Therefore, the diagnostic performance of BWS measurements was evaluated at two reference levels, 148 and 74 Bq $\mathrm{m^{-3}}$.

Prediction models for radon distributions

Pearson's correlation coefficients (not applied for potential non-linear relationships) were computed to determine the strength of the linear relationship between the ALAA radon concentration and: (1) BWS concentration, (2) the BY concentration and (3) the FFY concentration. Correlations were also examined between the CRE and these same three distinct distributions, and the ALAA. These comparisons were of interest to assess the tendency of the CRE to vary with each type of radon measurement. For instance, if a larger correlation coefficient was found between the CRE and the FFY measurements compared with the correlation coefficient with the BY measurements, this could be an indicator that a participant's actual radon exposure can be more closely approximated by an upper floor radon measurement compared with a basement measurement. Simple regression models were used to evaluate the predictive ability of the BWS screening measurements for the measured and

calculated annual distribution variables (BY, FFY, ALAA or CRE) (see the equation below).

$$\ln(\text{variable}) = \text{constant} + \text{slope} \times \ln(\text{BWS}) + \text{error} \quad (2)$$

$$\text{Variable} = e^{\text{constant}} \times (\text{BWS})^{\text{slope}} \times e^{\text{error}} \quad (2A)$$

Backward stepwise regression was used to evaluate the effects of housing and occupant factors on the BWS measurements' predictive performance with factors with P-values of <0.20 being retained in models. Details of similar models and analyses are available elsewhere[8].

RESULTS

Measured and calculated radon distributions

This study consists of 158 Iowa homes with a complete set of radon measurements (i.e. each home had measured and calculated distributions for BWS, BY, FFY, DFB, ALAA and CRE) (Table 1). Except for the absolute paired DFB, the data were found to be ln-normally distributed using the Shapiro–Wilks' test. Thus, statistical comparisons and tests were performed using ln-normal distribution statistics.

Within the home, spatial differences between the basement and non-basement radon concentrations were observed. The GM of the BWS measurements (199 Bq m^{-3}) was found to be approximately twice the GM of the FFY measurements (104 Bq m^{-3}). The statistical significance of this difference was confirmed by a paired t-test on the ln-transformed data. Both distributions had similar geometric standard deviations (GSDs) ($e^{\sigma} = 2$).

In the liveable area floors, radon concentration distributions (i.e. FFY and ALAA) were virtually identical. This is not surprising because 90 % of the living rooms and 75 % of the bedrooms were located on the non-basement first floor. The median value of the absolute paired difference between the FFY measurements and BWS (i.e. DFB) was 80 Bq m^{-3}. Instrumental variation could account for the seven BWS measurements that were lower than their matching FFY measurements.

Diagnostic performance of screening radon tests

The diagnostic performance of the BWS measurement for both ALAA and FFY measurements was almost identical so only the results for the ALAA concentrations are presented. The number of measurements in each diagnostic classification and the predictive value of the two possible test outcomes for two reference levels are presented in Table 2.

For this group of homes, the predictive value of a positive BWS measurement was only 44 % at the current US EPA radon action level of 148 Bq m^{-3}. This performance is not surprising given there was a larger proportion of results equal to or above the action level for BWS measurement (63 %) than the ALAA radon concentration (28 %) (Table 1). The predictive value of a positive BWS measurement improved to 72 % at a lower reference level of 74 Bq m^{-3}.

Annual average radon concentrations predicted by short-term radon measurements

A strong linear relationship was found between the ln(BWS) and the ln-transformed year-long radon measurements and CRE. For example, the correlation coefficient of ln(ALAA) ($r = 0.82$, $P < 0.0001$) indicates that 67 % (R^2) of the variability in the ln(ALAA) can be explained by the BWS measurements. Table 3 shows the regression parameters and standard errors of the regression model fit (Equation 2).

The regression fit (represented as solid line) to the ln-transformed ALAA data and 95 % confidence interval limits (represented as dashed lines) are shown in Figure 1. Confidence intervals (CIs) for the prediction can be calculated from the standard error of the estimate (SEE). The lower limit of the 95 % CI for an ALAA concentration prediction is approximately ($e^{-2 \times \text{SEE}}$) × ALAA whereas the upper limit is approximately ($e^{2 \times \text{SEE}}$) × ALAA. For example, if the ALAA concentration was 148 Bq m^{-3}, the 95 % CI would extend from 68 to 322 Bq m^{-3}.

Table 1. Characteristics of radon distributions from 158 residences in Iowa.

Characteristic	BWS (Bq m^{-3})	BY (Bq m^{-3})	FFY (Bq m^{-3})	DFB (Bq m^{-3})	ALAA (Bq m^{-3})	CRE (WLM)
Geometric mean (GSD)	199 (2.0)	181 (2.0)	104 (2.0)	—	104 (2.0)	9.4 (2.0)
Arithmetic mean (SD)	257 (217)	233 (206)	136 (121)	123 (146)	136 (121)	12 (10)
Median	185	186	95	80	100	8.5
Range	42–1331	32–1787	16–878	1–1073	16–848	2.6–77
Per cent ≥148 Bq m^{-3}	63	60	29	—	28	—

BWS, basement winter short-term; BY, basement year-long; FFY, first floor year-long; DFB, paired difference between FFY and BWS; ALAA, annual living area average; CRE, cumulative radon-related exposure.

The ln-transformed CRE was strongly correlated with all ln-transformed year-long radon measurements: ALAA ($r = 0.98$, $P < 0.0001$), FFY ($r = 0.98$, $P < 0.0001$) and BY measurements ($r = 0.88$, $P < 0.0001$). The correlation with ln-transformed BWS measurement was also significant ($r = 0.81$, $P < 0.0001$). A regression fit, shown in Figure 2, found that 65 % of the variation in the CRE distribution could be predicted by the BWS measurements. A greater variation in the CRE distribution could be predicted by the ALAA concentrations ($R^2 = 0.95$), FFY measurements ($R^2 = 0.95$) or BY measurements ($R^2 = 0.77$).

Table 2. Number of BWS diagnostic test predictions and the BWS diagnostic predictive values for year-long measurements in the living area (ALAA) at two different action levels.

BSW (Bq m^{-3})	ALAA (Bq m^{-3})		Test prediction	Predictive value (%)	95 % Confidence interval
	≥148	<148			
≥148	44	56	Positive	44	34–54
<148	1	57	Negative	98	91–100
	≥74	<74			
≥74	108	41	Positive	72	65–79
<74	0	9	Negative	100	—

Table 3. Regression parameters for predicting ln(year-long radon measurements) or ln(CRE) from ln(basement short-term radon measurements).

Variable	Constant (SE)	Slope (SE)	SEE	R^2
ALAA	0.20 (0.21)	0.84 (0.05)	0.41	0.67
FFY	0.23 (0.25)	0.83 (0.04)	0.41	0.67
BY	0.64 (0.21)	0.86 (0.04)	0.35	0.75
CRE	−1.60 (0.23)	0.72 (0.04)	0.37	0.65

SE, standard error; SEE, standard error of estimate; ALAA, annual living area average; FFY, first floor year-long; BY, basement year-long; CRE, cumulative radon-related exposure.

Improved predictions using housing and occupant factors

A large number of housing and occupant factors from the questionnaires were examined previously by Barros *et al.*[8] to assess their potential influence on the radon measurements, which was helpful to gain insight about the factors affecting the agreement between these measurements. However, only the ALAA regression factor analysis is presented here since the analyses of other year-long radon distributions were similar. The factors, which were found to be influential for the variables used in this study, are listed in Table 4.

The backward regression analysis using only housing and occupant factors found an increase in ALAA concentrations when the home: belonged to a lung cancer case, had central air conditioning and had a basement sump (Table 5). The factors that decreased the ALAA concentration included a home with a poured concrete foundation wall, the home had more than one floor above ground, the home had a window air conditioner in a non-basement area and if the participant was a current smoker. The final model's R^2 showed that 45 % of the variability in the ALAA concentration could be explained by these factors.

When the BWS measurements were added as a variable in the regression fit, the model's R^2 value increased to 80 % and the number and influence of the factors changed (Table 6). New factors that increased the ALAA concentration were if the home had: more than one major plumbing penetration in the basement, a clothe dryer in the basement and a forced air heating

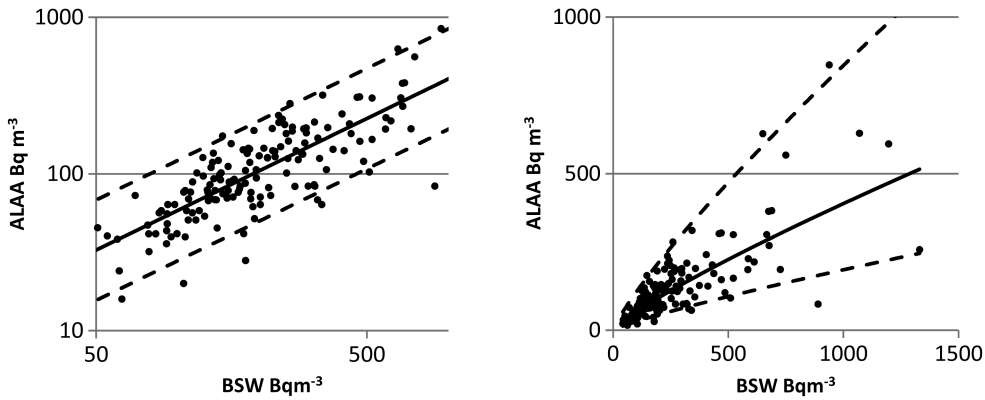


Figure 1. Annual living area average radon concentrations predicted from BWS measurements on log (left) and linear (right) scales.

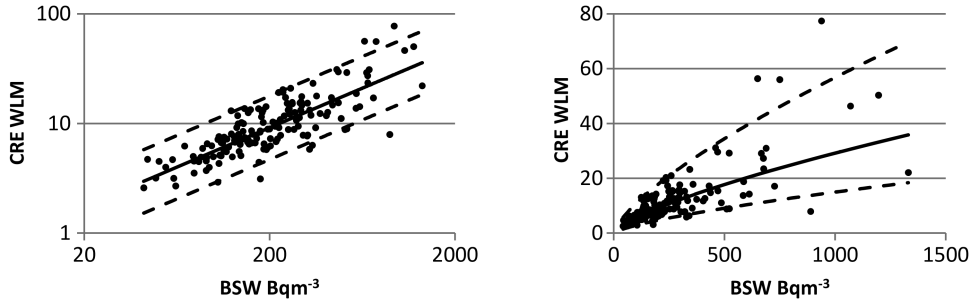


Figure 2. Cumulative radon-related exposure predicted from BWS measurements on log (left) and linear (right) scales.

system. The number of above-ground floors and a basement sump was no longer significant.

DISCUSSION

Radon distributions

The distributions of the short-term and year-long basement radon concentrations were similar to ~60 % of the BWS and 60 % of the BY concentrations being equal or exceeding the US EPA's radon action level of 148 Bq m^{-3}. On the upper floors, only about half of the year-long measurements (29 %) were equal to or exceeded the action level. This strong spatial radon variation from the basement to the non-basement first floor is highlighted by a large median difference (80 Bq m^{-3}).

The US EPA state radon survey for Iowa[17] observed a similar spatial trend in short-term measurements. In the US EPA survey, the GM (241 Bq m^{-3}) of 2-d winter screening radon measurements in 1208 basements was about twice the GM (134 Bq m^{-3}) of the 2-d screening measurements obtained in non-basement first floors in 166 residences. The percentage of screening tests above the action level in the basement was slightly higher in the US EPA survey (74 %) than the percentage equal to or above the action level in the present study (63 %).

Compared with this study, the US EPA survey showed more home-to-home variation. Their GSD (2.5) was significantly higher than the present study's GSD (2.0), which may reflect differences in measurement duration, detector precision or house sample characteristics. A New Jersey survey, which observed very low screening radon concentrations, found the GM of 4-d winter basement radon concentrations to differ to a larger degree (i.e. three times as large) from the annual average concentrations in non-basement living areas, usually a bedroom[7].

Diagnostic performance

The World Health Organization recommends a national reference radon level of 100 Bq m^{-3}[16]. Direct measurements of residential radon concentrations are the most reliable and practical method to determine whether a particular home exceeds recommended radon levels. Although an accurate assessment of whether the radon concentration in a home exceeds recommended levels would require long-term measurements in occupied living spaces, practical considerations, including limited time and resources, favour a mitigation decision-making protocol that is rapid, simple and effective. Basement winter short-term radon measurements are recommended by the US EPA as a first step in a radon diagnostic decision process[18]. If the screening test result is negative (i.e. below the action level), no further action is required. If the initial test equals or exceeds the action level (i.e. positive), additional radon testing is advised before a final decision is made.

Errors arising from an incorrect conclusion whether to proceed with action such as mitigation can occur due to misclassification from the short-term test (i.e. false negative or false positive). This misclassification can be attributed to temporal radon variation, spatial radon variation within the house and limited detector accuracy or precision. Only a few studies of the diagnostic performance of screening tests in different homes have been published. A nationwide study of 1449 homes performed by the US EPA, where the median radon concentration (48 Bq m^{-3}) in living spaces was about one-third of the US EPA's radon action level, 79 % of the short-term tests were negative and only 2.5 % were false negatives (i.e. short-term test was negative when the year-long test was positive)[19]. Seventeen per cent of the mean of two short-term tests were positive, and only 4 % were false positives (i.e. short-term test was positive when the year-long test was negative). However, in that same study, a subset of homes with year-long radon concentrations near the radon action level had higher misclassification (i.e. false positive) rates as high as 50 %.

In the present study, the median annual radon concentration on an upper level (95 Bq m^{-3}) was roughly twice that of the median annual concentration in the upper floors of the US sample, but only half of the median basement short-term radon concentration

Table 4. Summary of housing and occupant factors used in regression predictions for ln(ALAA) from 158 homes in Iowa.

Characteristic	*N* (%)	Mean (SD), median
Basement foundation wall material		—
Concrete block	82 (52)	
Poured concrete	45 (28)	
Neither concrete block nor poured concrete	31 (20)	
Case/control status of participant		—
Case	48 (30)	
Control	110 (70)	
Number of above-ground floors		2 (0.5), 2
One	76 (48)	
Two	78 (49)	
Three	4 (3)	
Number of major plumbing penetrations in basement		2 (0.9), 2
Missing	35 (22)	
Number of months of opening windows per year in non-basement		6 (3), 6
Missing	32 (20)	
Participant was current smoker		—
Yes	22 (14)	
No	136 (86)	
Percentage of basement below ground		82 (18), 90
Missing	8 (5)	
Presence of central air conditioning		—
Yes	112 (71)	
No	46 (29)	
Presence of clothes dryer in basement		—
Yes	96 (61)	
No	62 (39)	
Presence of crawl space in basement		—
Yes	72 (46)	
No	86 (54)	
Presence of forced air heating system		—
Yes	130 (82)	
No	28 (18)	
Presence of sump in basement		—
Yes	33 (21)	
No	122 (77)	
Missing	3 (2)	
Presence of window air conditioner in non-basement		—
Yes	97 (61)	
No	61 (39)	
Square feet of house		2056 (682), 1969
Volume of basement		5779 (2826), 5618

Table 5. Backward regression parameters (final model) for predicting ln(ALAA) from housing and occupant factors alone.

Characteristic	β coeff.[a] (SE[b])	Student's *t*-test (*P*)
Basement foundation wall material		
Concrete block	Ref.[c]	—
Poured concrete	−0.21 (0.15)	−1.4 (0.18)
Case/control status of participant		
Case	0.24 (0.17)	1.4 (0.16)
Control	Ref.	—
Number of above-ground floors	−0.34 (0.12)	−2.8 (0.01)
Participant was current smoker		
Yes	−0.75 (0.23)	−3.2 (0.002)
No	Ref.	—
Presence of central air conditioning		
Yes	0.67 (0.18)	3.7 (0.0004)
No	Ref.	–
Presence of sump in basement		
Yes	0.53 (0.17)	3.2 (0.002)
No	Ref.	—
Presence of window air conditioner in non-basement		
Yes	−0.26 (0.16)	−1.6 (0.11)
No	Ref.	—
R^2	0.45	
Adjusted R^2	0.40	

[a]Slope parameter estimate.
[b]Standard error.
[c]Reference category.

(186 Bq m^{-3}). A comparison of positive test diagnostic performance between the two studies is difficult since a second test was taken in the US sample following US EPA protocol when the initial test is positive[18]. Since only one test was taken in the present study, only a qualitative comparison of diagnostic performance is possible for positive tests. For this study, the predictive value of a single positive test was only 44 %, which means that only 44 % of those homes that tested positive actually had living space concentrations equal to or above the US EPA's action level of 148 Bq m^{-3}. The predictive value of a positive test increased to 72 % when this level was reduced by half (i.e. 74 Bq m^{-3}).

Overall, the misclassification rate was 36 % at the 148 Bq m^{-3} radon action level. In this study, the US EPA-recommended screening protocol was observed to be reliably protective in that in only one home did the ALAA concentration exceed both the action level and the BWS concentration[14]. Two studies of homes using 2-d short-term basement winter measurements in the nearby state of Minnesota also showed significant misclassification rates. In a 1989 study of 76 homes with a median annual average radon concentration of 96 Bq m^{-3}, the predictive value of a positive test result was 60 %[20]. The predictive value of a negative test was 90 %. In a later Minnesota study where the sample's long-term median radon

Table 6. Backward regression parameters (final model) for predicting ln(ALAA) given ln(BWS) and housing/occupant factors.

Characteristic	β[a] coeff. (SE[b])	Student's *t*-test (*P*)
Ln(basement short-term radon concentration)	0.83 (0.06)	13 (<0.0001)
Basement foundation wall material		
Concrete block	Ref.[c]	—
Poured concrete	−0.16 (0.10)	−1.6 (0.11)
Case/control status of participant		
Case	0.31 (0.10)	3.0 (0.004)
Control	Ref.	—
Number of major plumbing penetrations in basement	0.08 (0.05)	1.4 (0.16)
Presence of central air conditioning		
Yes	0.31 (0.12)	2.7 (0.01)
No	Ref.	—
Presence of clothes dryer in basement		
Yes	0.27 (0.11)	2.4 (0.02)
No	Ref.	—
Participant was current smoker		
Yes	−0.39 (0.15)	−2.7 (0.01)
No	Ref.	—
Presence of forced air heating system		
Yes	0.41 (0.14)	3.0 (0.004)
No	Ref.	—
Presence of window air conditioner in non-basement		
Yes	−0.14 (0.10)	−1.4 (0.16)
No	Ref.	—
R^2	0.80	
Adjusted R^2	0.78	

[a]Slope parameter estimate.
[b]Standard error.
[c]Reference category.

concentration was 110 Bq m^{-3}, the predictive value was 58 % for a positive test and 96 % for a negative test[11].

Predicting long-term radon concentrations

In addition to their use to classify homes for mitigation decisions, short-term measurements, like the BWS measurements, are often used by homeowners to predict either the average long-term radon concentrations in living spaces or the 'worst case' for a home's potential to have elevated radon concentrations in upper floors. Since screening measurements taken in conjunction with real-estate transactions are the most common type of radon measurement in the USA, it is important to evaluate the reliability and accuracy of these interpretations. The low predictive value of the positive diagnostic tests in the present study suggests that individuals would be likely to overestimate the upper floor radon concentrations if they simply used the basement short-term test result as an accurate measure of that radon concentration. The screening test was not the worst case in 4 % of the houses where the BWS measurement was less than the FFY measurement. However, the average difference in those cases was small (10 Bq m^{-3}).

Simple regression analysis shows that a model based on BWS measurements from the sampled houses could predict the ALAA concentration within a factor of 2.2 at a 95 % confidence level. At the median value of the ALAA concentration (i.e. 100 Bq m^{-3}), the 95 % CI would span from 44 to 227 Bq m^{-3}. In a nationwide sample of 480 US homes including 53 homes in Iowa, a regression analysis of 2-d screening measurements showed a similar accuracy for predicting the ALAA concentration[21]. The 95 % CI factor for winter measurements was 2.5. That study had roughly an equal number of basement and non-basement houses. Therefore, BWS measurements are not adequate if the ALAA concentration needs to be determined with greater accuracy than a factor of two.

Housing and occupant behaviour was examined in this study to determine the impact of these factors alone on the ALAA concentration or if they could improve the BWS measurement predictions. Only ~45 % of the ALAA variation could be explained by the factors alone compared with 67 % explained by the BWS measurement alone. When BWS measurements and the housing and occupant factors were combined, 80 % of the variation was accounted for by the model.

Predicting long-term exposure

Sometimes it may be important to estimate the long-term radon-related exposure (e.g. CRE) in all spaces that an individual may occupy rather than just the radon concentration in an occupied room. The findings from this study indicate that a participant's CRE can be more closely approximated by upper floor measurements ALAA concentrations or FFY measurements compared with BWS measurements or BY measurements. Given the sample of study participants were all women, these findings are not surprising since women tend to spend more time indoors in their home.

And, when indoors, they spend the majority of their occupancy in the non-basement first floor according to an analysis of the retrospective temporal and spatial mobility of participants from the IRLCS[1].

The correlation between these CRE estimates and the upper floor radon concentrations may not be as strong for men or other individuals who spend less time per day in the home. These findings are supported by a study by Harley *et al.*[3] that found first floor radon concentrations to be a better estimate of personal radon exposure than basement radon measurements. The average ratio of the personal radon monitor measurements to the first-floor stationary radon measurements was 0.71 (SD = 0.03) and was strongly correlated

($R^2 = 0.85$). The average ratio of personal to basement measurements, however, was 0.22 (SD = 0.04) and was much less correlated ($R^2 = 0.31$).

CONCLUSION

This study provides evidence that short-term radon measurements taken in the basement during the winter should not be relied on exclusively to estimate annual average radon concentrations on upper floors or to generate radon exposure assessments. This study provides insight into the degree of misclassification of radon exposure that would occur if the participant's exposure assessment was based solely on a short-term radon measurement obtained in an area that is infrequently occupied. The findings caution the use of surrogate measures to make recommendations for testing in the home for radon in living areas, and relying solely on a screening measurement to estimate the concentration of radon in the entire home.

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