

VARIATION IN YEARLY RESIDENTIAL RADON CONCENTRATIONS IN THE UPPER MIDWEST

Zugui Zhang,* Brian Smith,* Daniel J. Steck,[†] Qun Guo,[‡] and R. William Field,^{§**}

Abstract—It is well known that inhalation of ²²²Rn and ²²²Rn decay products increases the risk of lung cancer. While the occurrences of high radon areas in the United States are generally known, studies examining the temporal yearly radon variation in homes across different regions are lacking. This information is essential to assess the ability of a year-long radon measurement to predict the future radon concentration in a home or reconstruct the retrospective residential radon concentration. The purpose of this study is to help fill this gap by examining the temporal variation of residential radon concentrations in homes over several years as well as to explore factors that affect the yearly temporal variability of residential radon concentrations. The coefficient of variation was used as a measure of relative variation between multiple measurements performed across homes over several years. Generalized linear model analyses were applied to investigate factors affecting the coefficient of variation. The median coefficient of variation between the first and second test period was 12%, while a median coefficient of variation of 19% was found between the first and third test period. Factors impacting the coefficients of variation were found to vary for different types of homes and by floors of a home. This study provides important insights into the uncertainty of residential radon gas concentrations that can be incorporated into the sensitivity analyses for the risk estimates of both the North American and global pooling of residential radon studies to improve risk estimates.

Health Phys. 93(4):288–297; 2007

Key words: detector, alpha track; dosimetry; epidemiology; ²²²Rn

INTRODUCTION

LUNG CANCER has been the leading cause of cancer death in the United States for more than two decades. In 2006,

lung and bronchus cancer is estimated to account for 31% of all cancer deaths in males and 26% in females. The number of new lung cancer cases and lung cancer deaths in 2006, including bronchus, is projected to be 174,470 and 162,460, respectively (Jemal et al. 2006). Previous epidemiologic studies of underground uranium and hard-rock miners have clearly demonstrated that prolonged exposure to ²²²Rn and its decay products (radon) is a causative factor in the development of lung cancer. The findings in miners have been further supported by direct evidence from case-control epidemiologic studies of individuals residentially-exposed to radon (Field et al. 2000, 2002; Krewski et al. 2005, 2006; Darby et al. 2005, 2006). The United States Environmental Protection Agency (U.S. EPA 2003) estimates that approximately 21,000 people die each year in the United States from residential radon progeny exposure.

Retrospective assessment of radon and radon progeny exposure faces a series of difficulties and challenges (Field et al. 1996) including assessing the accuracy and precision of contemporary radon gas measurements, adjusting for temporal and spatial variation (Fisher et al. 1998) of residential radon concentrations, minimizing missing data due to inability to measure radon in previous houses, accounting for occupancy patterns/lifestyle factors, failing to consider the possible contribution of detector response to thoron, and measuring radon gas concentrations as a surrogate for radon progeny exposure.

The motivation for performing the present study was to collect information regarding yearly residential radon gas variation. Information on yearly radon variation is useful for assessing the degree of error involved in using a single radon measurement to reconstruct an individual's past radon exposure history. Such information can also be used to better characterize uncertainties in estimated radon exposures for analyses of residential radon studies, particularly in the application of regression calibration—a statistical method for adjusting risk estimates when exposures are measured with error (Field et al. 2000, 2002; Krewski et al. 2005, 2006; Darby et al. 2005, 2006; Fearn et al. in press). In addition, information

* Department of Biostatistics, College of Public Health, University of Iowa, Iowa City, IA; [†] Department of Physics, Saint John's University, Collegeville, MN; [‡] Channing Laboratory, Brigham and Women's Hospital and Harvard Medical School, Harvard University, Boston, MA; [§] Department of Occupational and Environmental Health, College of Public Health, University of Iowa, Iowa City, IA; ^{**} Department of Epidemiology, College of Public Health, University of Iowa, Iowa City, IA.

For correspondence contact: R. William Field, University of Iowa, College of Public Health, Department of Occupational and Environmental Health, 104 IREH, Iowa City, IA 52242, or email at bill-field@uiowa.edu.

(Manuscript accepted 28 March 2007)
0017-9078/07/0

Copyright © 2007 Health Physics Society

regarding long-term temporal variation is extremely important for determining whether the degree of radon variation is an explanatory variable in comparisons between findings based on contemporary gas-based measurements as compared to retrospective radon gas and progeny reconstruction using glass-based radon measurements from a novel detector previously described (Steck et al. 2002).

The primary experimental objective of this study was to quantify the degree of temporal radon variation in a subset of houses included in the Iowa Radon Lung Cancer Study (Field et al. 2000). Housing factors that affect the yearly temporal variation of radon concentrations in homes over time were also investigated. The Iowa Radon Lung Cancer Study (IRLCS) was a population-based, case-control epidemiologic study that evaluated the association between residential radon gas exposure and the incidence of lung cancer among females in the state of Iowa. One thousand twenty-seven Iowa houses were tested for radon as part of the IRLCS between the years of 1993 and 1997. Year-long radon measurements were performed on every floor of the houses (Field et al. 2000). In addition, detailed information about the construction of each house was collected both via mailed questionnaires and via field technician on-site assessment. The IRLCS is unique among residential radon case-control studies in that the inclusion criteria required participants to have lived in their current house for at least 20 years.

METHODS

Participant selection

IRLCS homes were chosen as the sampling frame for this study. In order to characterize the temporal variation of residential radon measurements, study subjects were asked after the initial first year of radon testing whether they would be interested in participating in additional follow-up years of radon testing in their home. As detailed in the original study (Field et al. 2000), eligible participants in the follow-up testing were females aged 40–84 years, who lived in their current residence for at least 20 years and did not make significant modifications to their house as a result of previous radon testing. One hundred thirty-three subjects agreed to one additional follow-up year of testing, and sixty-four agreed to two additional follow-up years of testing. In this article, “first test” refers to the first yearly radon test result, “second test” to the second yearly radon test result, and “third test” to the third yearly radon test result. It is important to note that the first and second tests were conducted in consecutive years during 1994–1997, and

the third tests were performed 4–5 years after the second tests, during the period 2001–2002.

Questionnaire instruments, detector placement, and participant follow-up contact

A mail-out questionnaire was sent to every participant prior to a house visit (Field et al. 2000). Participants were requested to complete the questionnaire in order to collect the information on house characteristics, heating and cooling systems, ventilation patterns, weatherization, as well as demographics, occupational history, occupational exposure to toxicants, both active and passive smoking history, drinking water sources, personal and family health history, and other factors that may affect the yearly residential radon concentrations. Detectors were placed on each floor of the house, including the basement and master bedroom. Subsequent to consent and receipt of the questionnaire, field technicians visited each study house to review the questionnaires for completeness. The field technicians then conducted an on-site residential assessment survey in order to record house floor plans, room location of detector placement, detector placement location within a room, house floor of placement, time and date of placement, and other housing characteristics that may affect the temporal or spatial distribution of radon within a residence.

The field technicians conducted a termination survey at the end of the first radon testing period to retrieve dosimetry. At the on-site termination visit, the participant or next-of-kin was administered a final questionnaire that assessed information on house-related or behavioral changes, such as use of air conditioning, which may have affected radon concentrations during the measurement period. To assess the degree of yearly radon variation, IRLCS subjects were asked if they would agree to the second year of radon testing. For those that agreed, detectors were placed in the exact location as the previous bedroom and basement placements. At the end of the second year of testing, subjects were sent postage-paid, pre-addressed envelopes so that they could return the detectors along with a short questionnaire requesting information on conditions that may have changed in the house that could have affected the residential radon concentrations.

Approximately five years after the first testing that was performed, subjects who performed the second testing were sent a letter assessing interest in the third testing. Subjects who agreed to take part in the third testing were sent detectors by mail and instructed to place them in the same locations within the master bedroom and basement as in the second testing. Field technicians contacted subjects one week after the detector mailings to ensure that the detectors were placed in the correct locations. Detectors that

were sent for the third testing followed the same protocol for retrieval as the second testing measurements.

Radtrak alpha track detectors (ATDs) (Landauer Inc., Glenwood, IL) were used to measure the integrated, year-long mean radon concentration for both the initial and second year of testing. For the third testing, alpha track detectors manufactured by the Minnesota Radon Project (MRP, Collegetown, MN) were donated by one of the authors (DJS) to obtain a year-long integrated radon measurement. In order to ensure inter-calibration between the two types of alpha track detectors, 25 pairs of the ATDs were exposed side-by-side during the final testing period. Eighteen of those ATD pairs were exposed at low to moderate radon concentrations for a year in houses. The remaining seven pairs were exposed to higher radon concentrations for 4 to 10 days in two different radon exposure facilities. Similar calibration comparisons have been conducted between these two types of ATDs yearly since 1988. As had occurred in the past, a regression analysis showed good correlation ($R^2 = 0.97$) between the two models for the 25 pairs exposed in this study.

Both manufacturers maintain separate calibrations for each batch of track registration material based on exposures in national calibration facilities, like the U.S. EPA Las Vegas, Bowser-Morner, and U.S. Department of Energy Environmental Measurements Laboratory (DOE EML) facilities. To be in compliance with the accepted standards, individual detectors must be within 25% of the accepted value. Thus, individual manufacturers' reported results may differ significantly from each other and still meet standards. In order to minimize this effect for our year-to-year comparison, a regression adjustment was made to the MRP detectors used in the final year-long measurement period, i.e., an indicator variable for MRP detector measurements was included in the regression models to account for potential mean differences in (log) radon measurements from the MRP and Landauer detectors.

The *effective time* between the first and second testing was calculated as the difference between the mid-points of the first test and second test measurement periods. Similarly, the effective time between the first and third testing is the length of time between the mid-points of first test and third test measurement periods. As mentioned previously, the measurement periods for the first and second testing were consecutive, while the third testing period was often performed 5 y after the first testing period. As an example of the calculation of effective time between different years of testing, consider a first test testing period of 12 April 1994 to 28 April 1995, and a second testing period of 28 April 1995 to 9 March 1996. The corresponding effective time between

these periods is computed as follows: second test mid-point – first test mid-point = 3 October 1995 – 19 October 1994 = 349 d = 0.95 y.

Similarly, for a third testing period of 14 December 2001 to 21 December 2002, the effective time from the first test is as follows: third test mid-point – first test mid-point = 18 June 2002 – 19 October 1994 = 2,799 d = 7.7 y.

Quality assurance/quality control

This study followed a strict quality assurance/quality control (QA/QC) plan instituted prior to radon measurement. The QA/QC plan followed the U.S. EPA recommendations, which included detailed protocols for receiving, tracking, editing, entering, and filing of study data, and a series of guidelines including: (1) external review of quality assurance, (2) quality assurance objectives for measurement data, (3) measurement procedures and sample custody, (4) calibration procedures and frequency, (5) analytical procedures, (6) data reduction, validation, and reporting, (7) internal quality control checks, (8) quality assurance audits and reports, (9) preventive maintenance of monitoring equipment, and (10) procedures used to assess measurement precision, accuracy, and completeness. In addition, a QA officer from outside the study periodically reviewed all aspects of radon measurement, including field procedures, data management, data collection, laboratory correspondence, data analyses, reports, and data archives. Additional details regarding the QA/QC plan are available elsewhere (Field et al. 1998).

Data analysis

The coefficient of variation (COV) was calculated as a measure of relative variation between multiple radon measurements in different years from detectors placed in the same location. As a baseline measure of detector precision, the COV for measurements obtained from collocated detectors was also calculated. The COV for a set of measurements was calculated using the following formula:

$$COV = 100 \times SD/\bar{X}, \quad (1)$$

where SD is the standard deviation and \bar{X} is the arithmetic mean of the measurements. In this study, two COVs were calculated for each location at which detectors were placed, one for variation between first test and second test measurements, and the other for the variation between first test and third test measurements.

The COVs for first test vs. second test and first test vs. third test are the primary outcome measures of temporal variation. Generalized linear regression models

were used to identify and estimate the effect of important housing factors on the COVs. For the regression analysis, a gamma distribution with a log link was used. The gamma distribution was chosen because it is characteristic of the behavior generally exhibited by the COV; namely, it is right-skewed and has only positive values. In addition, the use of the gamma distribution is consistent with other similar studies (Lubin et al. 2005; Pang et al. 2005). Housing and other factors, such as the month and year of detector placement, were considered as potential covariates. The generalized linear models used for the analyses are of the form

$$COV_{ij} \sim \text{Gamma}(v, \mu_{ij}/v) \quad (2)$$

$$\log(\mu_{ij}) = \boldsymbol{\beta}' \mathbf{X}_{ij}, \quad (3)$$

where COV_{ij} is the coefficient of variation between the first test and second ($j = 2$) or third ($j = 3$) test for the i th location, and the gamma distribution is parameterized such that the mean and variance are $E(COV_{ij}) = \mu_{ij}$ and $\text{var}(COV_{ij}) = \mu_{ij}^2/v$, respectively. \mathbf{X}_{ij} is a vector of regression covariates that affect the COVs, and $\boldsymbol{\beta}$ is a vector of estimated regression parameters. Parameters estimates and standard errors are obtained via a generalized estimating equations (GEE) approach, which accounts for the correlation in the COV_{ij} s obtained from the same house (Zeger et al. 1988). A constant correlation between COVs from the same house is assumed for the GEE analysis.

Since the yearly variation in radon concentrations is related to the types of houses and floors, the analyses were conducted for 2 groupings of house floors (basement, and upper-floor defined as first floor and above) crossed with 2 groupings of house types (houses with one story, and houses with more than one story). Effective time was included as a covariate in all multivariate regression models and backward variable selection was conducted to choose other potential predictor variables for inclusion. Variables with p -values less than 0.20 were retained in the variable selection. Analyses were carried out using the SAS (Cary, NC) and S-Plus (Seattle, WA) statistical software programs.

RESULTS

Following the first test of radon measurements that occurred during 1994–1997, radon detectors were placed in the houses of 197 participants for a second consecutive year of testing. On average, two detectors per house were placed, for a total of 378 radon detectors. Four to five years after the second radon testing (2001–2002), 64 subjects agreed to perform a third year of radon testing. In the third year of testing, 125 radon detectors were

placed at the 64 houses. Each house had a basement and had been occupied by current residents for at least 25 y.

Radon measurements with an exposure period of less than 300 d ($n = 19$) as well as one outlier were excluded from the analyses. A minimum exposure period of 300 d was chosen to avoid including radon measurements not representative of a yearly mean residential radon concentration. In addition, one basement measurement had a radon concentration of 207 Bq m^{-3} (5.6 pCi L^{-1}) in first test and 932 Bq m^{-3} (25.2 pCi L^{-1}) in second test. The second test measurement was excluded from the final analyses as an outlier because of suspicion it may have been placed in a basement location that differed from the first test placement. After these exclusions, 375 second testing period measurements from 196 houses and 107 third radon testing measurements from 61 houses were available for the analysis of temporal variation. The majority of houses were either one or two stories (Table 1). The number of three-story houses was quite small ($n = 10$ for second test and $n = 4$ for third test), and hence they were placed in the same category as two-story houses for the data analyses.

Housing stock design and construction

The histogram plots in Fig. 1 show the distribution of year of house construction for the first/second tests and third test, respectively. Based on the histograms in Fig. 1 and the years that the homes were constructed, the cut-points were set up to group the homes. Given that the first test was conducted during 1994–1995, 1960 (a home built in this year was about 35 years old in 1994–1995) was chosen as the first cut point, which corresponds to the time after which more modern construction techniques were used; 1945 (a home built in this year was about 55 years old in 1994–1995) is the second cutpoint, which is around the time that the great depression ended and World War II came to the end. The third cutpoint is 1900 (a home built in this year was about 95 years old in 1994–1995), which marks the turn of the century and the introduction of some advanced construction technologies. As a result, the distribution of number of houses and measurements for the cutpoints is as follows: after 1960 ($n = 51$ number of houses, $N = 96$ number of measurements); 1945~1960 ($n = 55$, $N =$

Table 1. Number of study participants by type of house and radon testing period.

Type of house	Second test Number of houses	Third test Number of houses
One-story	98	31
Two-story	88	26
Three-story	10	4
Total	196	61

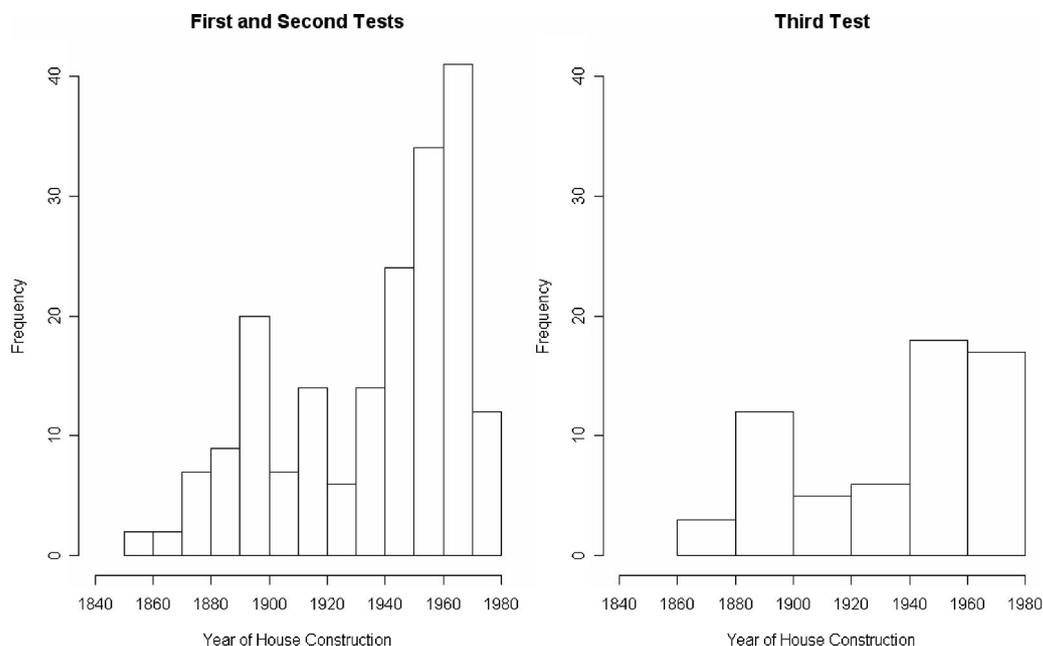


Fig. 1. Histogram plots for the year of house constructions.

105); 1900~1944 ($n = 50$, $N = 97$); and prior to 1900 ($n = 40$, $N = 77$). In the first and second tests, the mean year of house construction is 1935 with a standard deviation of 30.7, and it ranges from 1850 to 1974. For the third test houses in particular, the mean year of house construction is 1937 with standard deviation of 28.6, and it ranges from 1875 to 1974.

The year of house construction is an important potential confounding factor since home construction generally differs over time. To account for the effect of year of house construction, we have included the aforementioned categorization of year of house construction as an explanatory variable in all regression models.

In order to characterize the type of housing construction found among our sample of homes, the following summary statistics are provided. One hundred sixty-nine houses out of 196 had insulated ceilings (three of the houses had missing data). Among the third test houses, 56 of them had insulated ceilings and 4 did not have them. With respect to crawl space materials, 55 of the 64 houses had dirt floor material and 132 had missing data. A dirt crawl space was present in 14 of the 17 third test houses. For level one construction materials, 179 of the 196 houses had poured concrete. Fifty-five of the 57 third test houses had poured concrete material. For the construction materials used in level one foundations, the distribution of the number of the houses was as follows: wood (6), brick (11), poured concrete (55), stone (16), concrete block (93), and other (14); for the third test houses, the sample sizes were as follows: wood (3), brick

(2), poured concrete (19), stone (4), concrete block (28), and other (4).

Distribution of radon concentrations

Table 2 presents the radon concentrations by type and floor of houses. In the first test, radon concentrations ranged from 11 Bq m^{-3} (0.3 pCi L^{-1}) to 992 Bq m^{-3} (26.8 pCi L^{-1}) with the highest concentrations occurring in basements. The second test and third test period radon concentrations followed the same distribution with the highest concentrations occurring in the basement. For the third test there are 23 basement measurements and 34 first floor measurements in one-story houses. Among these 11 measurements, 2 were obtained from 2 slab-on-grade houses, and 9 were obtained from 7 houses with crawlspaces. The Wilcoxon Rank Sum test was used to examine the differences in radon concentrations between one- and two-story houses for basements and first floors, respectively. For basement radon measurements, there was a significant difference in the median radon concentrations between one- and two-story houses for second test ($p = 0.03$), but there were no significant differences found between one- and two-story houses for first test ($p = 0.07$) and third test ($p = 0.18$). Analyses indicated that for the first floor radon measurements, there were significant differences between the median radon concentrations for one- and two-story houses for first test ($p = 0.032$), second test ($p = 0.006$), and third test periods ($p = 0.042$).

Table 2. Descriptive statistics for ^{222}Rn concentrations (Bq m^{-3}) measured for one- and two-story houses in Iowa by type of house and floor.

Type of house/floor	Test (<i>n</i>)	Range	Median	Mean (SD)
One-story basement	First test (83)	26–992	222	242 (171)
	Second test (83)	19–1006	218	258 (189)
	Third test (23)	70–682	222	236 (132)
One-story first floor	First test (102)	11–681	115	143 (106)
	Second test (102)	11–633	126	161 (121)
	Third test (34)	48–499	166	193 (115)
Two-story basement	First test (87)	22–803	155	216 (192)
	Second test (87)	19–736	159	203 (164)
	Third test (24)	30–536	171	188 (118)
Two-story first floor	First test (57)	11–422	85	108 (80)
	Second test (57)	19–296	85	106 (71)
	Third test (13)	33–399	88	126 (110)
Two-story second floor	First test (46)	11–259	59	81 (64)
	Second test (46)	11–292	74	94 (76)
	Third test (13)	20–210	138	120 (70)

Correlation between testing periods

Table 3 presents the correlation coefficients between testing periods by both house type and floor.

All housing types. The Spearman correlations for the first vs. second test period, first vs. third test period, and second vs. third test period measurements are presented in Table 3 by floor and house type. For all housing types, the correlation coefficients for the first vs. second test were the same for basements (0.94), first floors (0.94), and second and above floors (0.94). Spearman correlation coefficients for other testing period comparisons exhibited greater variation ranging from 0.82 (second vs. third test for second and above floors) to 0.90 (first vs. third test for second and above floors).

One-story housing types. Spearman correlation coefficients for first vs. second test were in close agreement for basement (0.94) and first floor radon measurements (0.93); while the first vs. third test and the second vs. third test exhibited greater variation that ranged from 0.78 (second test vs. third test for first floor) to 0.87 (first test vs. third test for basement).

Two-story housing types. The correlation coefficients for the first vs. second test were similar for basements (0.93), first floors (0.94), and second and above floors (0.94). The correlation coefficients for the first vs. third test and second vs. third test exhibit a greater range of variation with a low of 0.80 (second test vs. third test for basement) to a high of 0.95 (first test vs. third test for first floor).

Coefficient of variation for temporal radon measurements

Table 4 presents a summary of the COVs in terms of test periods (first test vs. the second and third tests) by both type and floor of house. Overall, for all housing types, the median COV was higher for the first vs. third test period as compared to the first vs. second test period. In addition, for all housing types, the median COV was identical for the first vs. second test for median radon concentrations above and below 150 Bq m^{-3} , while a greater variation in the COV was noted between the first and third test particularly for homes with radon concentrations below 150 Bq m^{-3} .

Table 3. Correlation coefficients for measurements by test periods and floors.

Test	Type of house	Floor		
		Basement	First floor	2 nd and above floors
First test vs. second test	All types of houses	0.94	0.94	0.94
	One-story house	0.94	0.93	
	Two-story house	0.93	0.94	0.94
First test vs. third test	All type of houses	0.83	0.84	0.90
	One-story house	0.87	0.78	
	Two-story house	0.81	0.95	0.90
Second test vs. third test	All types of houses	0.83	0.85	0.82
	One-story house	0.85	0.80	
	Two-story house	0.80	0.94	0.82

Table 4. Coefficient of variation for radon measurements by housing type and floor.

Type of house/floor	Test (<i>n</i>)	Year			COV (%) Median	
		COV (%) Range	COV (%) Mean (SD)	COV (%) Median	≤150 Bq m ⁻³	>150 Bq m ⁻³
All houses	First vs. second (375)	0–74	15 (13)	12	12	12
	First vs. third (107)	0–110	24 (21)	19	23	17
Type of house/floor (<i>n</i>)						
One-story	First vs. second (83)	1–52	14 (11)	11	11	12
Basement	First vs. third (23)	0–45	17 (16)	11	37	9
One-story	First vs. second (102)	0–74	16 (13)	13	12	15
First floor	First vs. third (34)	3–110	27 (24)	19	26	14
Two-story	First vs. second (87)	1–68	17 (14)	13	14	5
Basement	First vs. third (24)	2–87	27 (18)	23	23	24
Two-story	First vs. second (57)	0–63	13 (14)	10	10	3
First floor	First vs. third (13)	1–53	15 (14)	10	9	19
Two-story	First vs. second (46)	0–60	17 (14)	13	13	11
Second floor	First vs. third (13)	5–93	32 (24)	28	30	27

Table 5 displays the temporal change, assessed by the COV, in radon by type of home and floor. The greatest degree of change in radon concentration was noted for two-story houses between the first and third test with only 38.5% of the homes exhibiting a COV ≤25%. Alternatively, over 80% of the basement radon measurements in one-story houses yielded a COV ≤25%. Overall, radon measurements from the first test as compared to the third test, for both one- and two-story houses, displayed much lower agreement.

Factors affecting the coefficient of variation

Generalized linear regression was used to model the temporal variation, expressed in COV, as a function of select housing factors, the effective time between testing periods, and the type of detector. The *a priori* selected factors used for this analysis were effective time between testing periods, finished/unfinished basement, type of heating system (forced air, etc.), presence/absence of a resident that smoked in the bedroom, presence/absence of current smokers in residence, presence/absence of insulated ceiling materials, year of house construction,

percentage of basement underground, first floor flooring material, presence/absence of a crawl space under any portion of house, presence/absence of a major plumbing penetration (e.g., toilet stool, bathtub, shower, hot tub, or washing machine) in the basement, number of months of fireplace usage, crawl space floor construction materials, first floor foundation wall construction materials, location of lowest home level relative to the ground, presence/absence of attic fan in residence, presence/absence of central air conditioning, presence/absence of window air conditioning, opening of windows, volume of basement (cubic feet), and house within/outside city limits. Backward variable selection was conducted to choose potential predictor variables for inclusion in the multivariate regression models.

The following variables with *p*-values larger than 0.20 from the backward variable selection that were excluded from the multivariate regression models were: presence/absence of attic fan in residence, presence/absence of central air conditioning, presence/absence of window air conditioning, presence/absence of current

Table 5. Percent of sites having radon measurements with coefficient of variation (COV) less than 10%, 20%, or 25% by type of house and floor.

Type of house/floor	Test (<i>n</i>)	Percent of floors with COV ≤10%	Percent of floors with COV ≤20%	Percent of floors with COV ≤25%
One-story basement	First vs. second (107)	44.6%	77.1%	83.1%
	First vs. third (23)	47.8%	65.2%	69.6%
One-story first floor	First vs. second (102)	37.3%	68.6%	84.3%
	First vs. third (34)	29.4%	50.0%	58.8%
Two-story basement	First vs. second (87)	37.8%	72.4%	79.3%
	First vs. third (24)	16.7%	41.7%	54.2%
Two-story first floor	First vs. second (57)	47.4%	78.9%	86.0%
	First vs. third (13)	46.2%	84.6%	84.6%
Two-story second floor	First vs. second (46)	37.0%	67.4%	76.1%
	First vs. third (13)	23.1%	30.8%	38.5%

Table 6. Estimated relative mean (95% CI) change in COV for the generalized estimation equation analysis of basement measurements in one-story houses.

Predictor	(n)	Relative mean COV
Time (1-y increase)		1.04 (0.96–1.12)
Basement		
finished	(31)	0.48 (0.29–0.79)
unfinished	(52)	1.00 ^a
Type of heating system		
forced air furnace	(66)	0.94 (0.34–2.60)
radiator	(13)	1.00 ^a
Insulated ceiling		
present	(77)	0.27 (0.17–0.42)
not present	(3)	1.00 ^a
Year of house construction		
after 1960	(31)	0.91 (0.43–1.94)
1945~1959	(35)	1.17 (0.59–2.31)
1900~1944	(12)	0.97 (0.44–2.13)
prior to 1900	(5)	1.00 ^a

^a Reference category.

smokers in residence, opening of windows, volume of basement (in cubic or in square feet), and house within/outside of city limits. Factors that remained in the model are discussed below by housing types and floors.

One-story houses

Basement measurements. Factors selected, based on the GEE analysis, as important predictors of temporal radon changes for basement measurements are listed in Table 6 and include effective time between testing periods, finished/unfinished basement, type of heating system, the presence or absence of insulated ceiling materials, and year of house construction. A significant relative decrease of 0.48 [95% confidence interval (CI) 0.29–0.79] in the mean COV for finished basement relative to unfinished basement was noted. There was a significant decrease in the mean COV associated with insulated ceiling materials of 0.27 (95% CI 0.17–0.42).

First floor measurements. Factors selected as important predictors, based on the GEE analysis, of COV for first floor measurements are listed in Table 7 and include effective time between testing periods, percentage of basement underground, the presence of a crawl space under any portion of house, and year of house construction. For each increased year between radon testing, the COV significantly increased by a factor of 1.08 (95% CI 1.00–1.12). The presence of a crawl space significantly increased by 1.51 (95% CI 1.11–2.06) the mean COV.

Two-story houses

Basement measurements. Factors selected as important predictors, based on the GEE analysis, of COV

Table 7. Estimated relative mean (95% CI) change in COV for the generalized estimation equation analysis of first floor measurements in one-story houses.

Predictor	(n)	Relative mean COV
Time (1-y increase)		1.08 (1.00–1.12)
% basement underground (10% increase)		1.01 (0.97–1.05)
Crawl space present		
yes	(33)	1.51 (1.11–2.06)
no	(69)	1.00 ^a
Year of house construction		
after 1960	(41)	1.18 (0.61–2.29)
1945~1959	(39)	1.04 (0.54–1.99)
1900~1944	(16)	0.80 (0.40–1.59)
prior to 1900	(6)	1.00 ^a

^a Reference category.

for basement measurements are listed in Table 8 and include effective time between testing periods, presence of a major plumbing penetration (e.g., toilet stool, bathtub, shower, hot tub, or washing machine) in the basement, insulation present in the ceiling, the number of months of fireplace usage, and year of house construction. For each increased year between radon testing, the COV significantly increased by a factor of 1.08 (95% CI 1.04–1.16). A significant increase of 1.54 (95% CI 1.11–2.14) in COV was also found for the presence of a toilet stool, bathtub, shower, or hot tub; while the presence of insulation in the ceiling significantly reduced the variation to 0.64 (95% CI 0.42–0.97).

Above-ground measurements. Factors selected as important predictors of COV for above-ground measurements are listed in Table 9 and include effective time between testing periods, crawl space floor construction materials, location of lowest home level relative to the

Table 8. Estimated relative mean (95% CI) change in COV for the generalized estimation equation analysis of basement measurements from two-story houses.

Predictor	(n)	Relative mean COV
Time (1-y increase)		1.08 (1.04–1.16)
Toilet, bathtub, shower, washing machine, or hot tub in basement		
present	(62)	1.54 (1.11–2.14)
not present	(25)	1.00 ^a
Insulated ceiling		
present	(70)	0.64 (0.42–0.97)
not present	(17)	1.00 ^a
Fireplace usage (1-mo increase)		1.06 (0.97–1.15)
Year of house construction		
after 1960	(9)	1.29 (0.79–2.09)
1945~1959	(14)	1.14 (0.72–1.82)
1900~1944	(36)	0.95 (0.68–1.33)
prior to 1900	(28)	1.00 ^a

^a Reference category.

Table 9. Estimated relative mean (95% CI) change in COV for the generalized estimation equation analysis of above ground measurements from two-story houses ($n = 103$).

Predictor	(n)	Relative mean COV
Time (1-y increase)		1.12 (1.00–1.20)
Crawl space floor construction material		
dirt	(64)	0.51 (0.33–0.81)
poured concrete	(6)	1.00 ^a
Location of lowest home level, relative to the ground		
entirely below ground	(11)	3.11 (1.13–8.53)
walkout basement with 2 sides partially below ground	(85)	1.00 ^a
Fireplace usage (1-mo increase)		0.99 (0.86–1.15)
Year of house construction		
after 1960	(15)	2.01 (0.70–5.75)
1945–1959	(17)	4.30 (2.12–8.73)
1900–1944	(33)	1.04 (0.61–1.75)
prior to 1900	(38)	1.00 ^a

^a Reference category.

ground, the number of months of fireplace usage, and year of house construction. For each increased year between testing periods, the COV significantly increased by a factor of 1.12 (95% CI 1.00–1.20). For crawl space floor construction materials, the decrease in the mean COV for dirt, relative to poured concrete, was 0.51 (95% CI 0.33–0.81). A significant COV increase of 3.11 (95% CI 1.13–8.53) for homes with entirely below-ground basements relative to those with walkout basements having two sides partially below ground was found. In addition, for year of house construction, the COV significantly increased by a factor of 4.30 (95% CI 2.12–8.73) for houses built between 1945 and 1960, relative to houses built prior 1900.

DISCUSSION AND CONCLUSION

The correlation between radon measurements for the various testing periods, especially for the first test period vs. the second test period, was fairly strong. Nonetheless, the temporal radon variation was substantially greater than the intrinsic detector imprecision. Earlier work by Field et al. (1998) observed a mean COV of 6.9% for the collocated alpha track detectors used in the Iowa Radon Lung Cancer Study. In this study, the COVs for individual homes for the repeated testing periods ranged from 0 to 74% for the first testing period and from 0 to 110% (Table 4) for the second testing period. The mean COV between radon measurements was also higher for the first vs. third test period for all home types and floors.

The results from the generalized estimation equation analysis indicated that the most significant factor affecting the COV was the effective time between testing periods. The other significant factors influencing the

temporal radon variation, expressed in COVs, vary based both on the type of house and by floor. The most common factors that generally increased the variation of radon over time, at least for some floors and house types, included an unfinished basement; lack of an insulated ceiling; the presence of a crawl space; basement entirely below ground level; presence of a toilet, washing machine, or bathtub (plumbing penetration) in the basement; poured concrete as opposed to a dirt basement floor; poured concrete crawl space floor as opposed to soil; and limited fireplace usage. The only factor that showed a consistent statistically significant relative increase in the basement radon variation for both one- and two-story homes was the absence of insulation in the ceiling of the home.

This study provides important insights that allow investigators to perform sensitivity analyses and improve risk estimates for residential radon studies by adjusting for some of the uncertainty in radon measurements over time. The findings of this study also suggest that the validity of the regression calibrations, which are often used to address some of the retrospective radon measurement errors (Darby et al. 2005, 2006), may be improved by modeling the varying change in temporal radon concentration by housing factors. Further studies are required to assess whether or not these factors, affecting the temporal radon variation, are similar to the factors affecting the temporal variation of radon across different geographic regions.

Acknowledgments—Supported by grant numbers RO1 ES05653 and P30 ES05605 from the National Institute of Environmental Health Sciences and RO1 CA85942 from the National Cancer Institute, National Institutes of Health.

REFERENCES

- Darby S, Hill D, Auvinen A, Barros-Dios, JM, Baysson H, Bochicchio F, Deo H, Falk R, Forastiere F, Hakama M, Heid I, Kreienbrock L, Kreuzer M, Lagarde F, Makelainen I, Muirhead C, Oberaigner W, Pershagen G, Ruano-Ravina A, Ruostenoja E, Rosario AS, Tirmarche M, Tomasek L, Whitley E, Wichmann HE, Doll R. Radon in houses and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. *British Med J* 330:218–223; 2005.
- Darby S, Hill D, Auvinen A, Barros-Dios JM, Baysson H, Bochicchio F, Deo H, Falk R, Forastiere F, Hakama M, Heid I, Kreienbrock L, Kreuzer M, Lagarde F, Makelainen I, Muirhead C, Oberaigner W, Pershagen G, Ruano-Ravina A, Ruostenoja E, Rosario AS, Tirmarche M, Tomasek L, Whitley E, Wichmann HE, Doll R. Indoor radon and lung cancer. *Epidemiol* 17:121–122; 2006.
- Fearn T, Hill DC, Darby SC. Measurement error in the explanatory variable of a binary regression: regression calibration and integrated conditional likelihood in studies of residential radon and lung cancer. *Statistics in Med* (in press).

- Field RW, Smith BJ, Steck DJ, Lynch CF, Brus CP, Neuberger JS, Kross BC. Residential radon-222 exposure and lung cancer: exposure assessment methodology. *J Exposure Analysis Environmental Epidemiol* 6:181–195; 1996.
- Field RW, Lynch CF, Steck DJ, Fisher EL. Dosimetry quality assurance: Iowa residential radon lung cancer study. *Radiat Protect Dosim* 78:295–303; 1998.
- Field RW, Steck DJ, Smith BJ, Brus CP, Neuberger JS, Fisher EF, Platz CE, Robinson RA, Woolson RF, Lynch CF. Residential radon gas exposure and lung cancer: the Iowa radon lung cancer study. *Am J Epidemiol* 151:1091–1102; 2000.
- Field RW, Smith BJ, Steck DJ, Lynch CF. Residential radon exposure and lung cancer: variation in risk estimates using alternative exposure scenarios. *J Exposure Analysis Environmental Epidemiol* 12:197–203; 2002.
- Fisher EL, Field RW, Smith BJ, Lynch CF, Steck DJ, Neuberger JS. Spatial variation of residential radon concentrations: the Iowa radon lung cancer study. *Health Phys* 75:506–513; 1998.
- Jemal A, Siegel R, Murray T, Ward E, Xu J, Smigal C, Thun M. Cancer statistics, 2006. *CA Cancer J Clin* 56:106–130; 2006.
- Krewski D, Lubin JH, Zielinski JM, Alavanja M, Catalan VS, Field RW, Klotz JB, Letourneau EG, Lynch CF, Lyon JI, Sandler DP, Schoenberg JB, Steck DJ, Stolwijk JA, Weinberg C, Wilcox HB. Residential radon and risk of lung cancer—a combined analysis of 7 North American case-control studies. *Epidemiol* 16:137–145; 2005.
- Krewski D, Lubin JH, Zielinski JM, Alavanja M, Catalan VS, Field RW, Klotz JB, Letourneau EG, Lynch CF, Lyon JI, Sandler DP, Schoenberg JB, Steck DJ, Stolwijk JA, Weinberg C, Wilcox HB. A combined analysis of North American case-control studies of residential radon and lung cancer. *J Toxicol Environmental Health* 69:533–597; 2006.
- Lubin JH, Wang ZY, Wang LD, Boice JD, Cui HX, Zhang SR, Conrath S, Xia Y, Shang B, Cao JS, Kleinerman RA. Adjusting lung cancer risks for temporal and spatial variations in radon concentration in dwellings in Gansu province, China. *Radiat Res* 163:571–579; 2005.
- Pang WK, Leung PK, Huang WK, Liu W. On interval estimation of the coefficient of variation for the three-parameter Weibull, lognormal and gamma distribution: a simulation-based approach. *European J Operational Res* 164:367–377; 2005.
- Steck DJ, Alavanja MCR, Field RW, Parkhurst MA, Bates DJ, Mahaffey JA. ²¹⁰Po implanted in glass surfaces by long term exposure to indoor radon. *Health Phys* 83:261–271; 2002.
- United States Environmental Protection Agency. Air and radiation (6608J), EPA assessment of risk from radon in houses. Washington, DC: U.S. EPA; EPA 402-R-03-003; 2003.
- Zeger SL, Liang KY, Albert P. Models for longitudinal data: a generalized estimating equation approach. *Biometrics* 44:1049–1060; 1988.

