YEAR-TO-YEAR INDOOR RADON VARIATION

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ABSTRACT

Year-long measurements of contemporary indoor radon concentrations have been used as the "gold standard" by homeowners to estimate future radon exposure and by epidemiologists to retrospectively reconstruct past exposures. Random variations and persistent temporal trends can affect remedial action decisions and the accuracy of the risk coefficients derived from epidemiological studies. Seventeen hundred year-long indoor radon measurements were made at 196 sites in 98 Minnesota houses from 1983 to 2000 to determine year-to-year radon fluctuations and long-term temporal trends. The typical site had 10 year-long measurements over 13 years and showed year-to-year variations of 26%. Climate, exposure to wind, and radon concentration affected year-to-year variation, but house age, construction, or measurement floor did not. Some individual sites showed significantly larger radon changes when modifications were made to the house structure and heating-ventilation systems.

INTRODUCTION

Long-term exposure to elevated radon (^{222}Rn) concentrations has been linked to increased lung cancer risk. Recent case-control epidemiologic studies of residentially-exposed individuals use year-long measurements of contemporary radon concentrations as the "gold standard" to estimate exposures over past decades (Field et al. 2000, 2002; Krewski et al. 2005, 2006; Darby et al. 2005, 2006). Radon may vary from year-to-year either in response to environmental fluctuations or changes in the home's structure, heating-cooling-ventilation components, and occupants. The accuracy of the radon-related risk coefficients derived from epidemiological studies depends on the magnitude of these variations. Homeowners and public health officials also rely on contemporary radon measurements to assess future radon-related risks. The decision to take remedial action is usually based on measurements that cover a short period compared to the potential exposure time. An inappropriate decision may be made if the radon concentration during the measurement period is not representative of the future average, either due to a temporary fluctuation or a persistent trend. At present, little is known about the long-term trends or variation of residential radon as only a few longitudinal studies of radon changes in small groups of regional homes have been reported (Martz et al. 1991; Steck 1992).

The primary goals of this study were to determine the magnitude and causes of year-to-year radon variations in a representative group of houses in central North America. The study period and houses were chosen to reflect the relevant exposure period and structures found in radon-lung cancer studies.

METHODS

Sampling sites

Year-long radon gas measurements were made in 106 single-family houses in Minnesota during the period 1983–2000 (Steck 1990, Steck 1992). Figure 1 shows the average radon concentration of the homes as shaded postal code areas. The houses were randomly recruited and belonged to science teachers, college alumni, or their neighbors. An equal number of houses from towns and rural areas throughout Minnesota were measured. At least one adult occupant remained the same throughout the survey. In each house, annual average radon concentrations were measured at sites in the two lowest levels. The author installed the detectors in the first measurement year during a visit to select the two sites for monitoring. In subsequent years, the detectors were exchanged by mail.

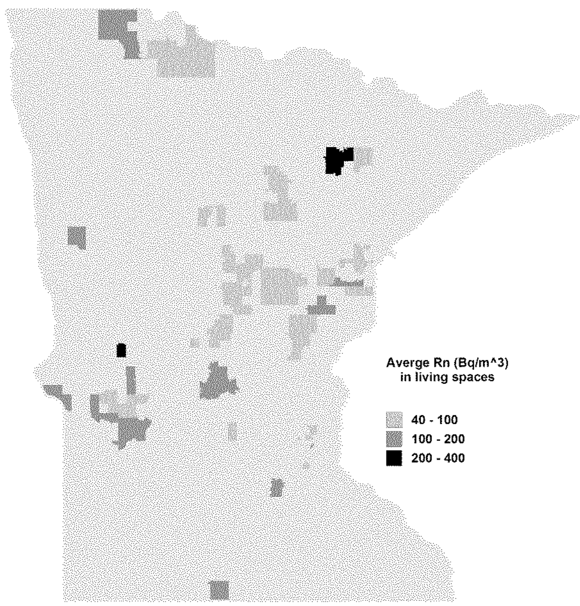

Figure 1 The postal code areas of the homes area shaded to show the average radon concentration of that cluster.

Year-long radon concentration measurements

Radon measurements were made with ATDs that have a 2-cm^2 chip of dosimetry grade CR-39 enclosed in a small plastic chamber. Each batch of track registration material underwent an annual calibration test to identify potential changes in efficiency. This calibration took place in a large volume radon chamber monitored by calibrated, continuous radon monitors. This local calibration was validated, almost every year, by exposures in national radon chambers (US DOE EML, UNC GEOTECH, Bowser-Morner, US EPA NAREL and R&IENL), usually as part of a radon gas detector intercomparison exercise conducted by the USDOE, the USEPA, or AARST. The detector was listed as meeting proficiency requirements as part of the USEPA Radon Measurement Proficiency Program. An historical sample of detectors was reread in 1999 to judge the variation of the author's track-recognition reproducibility over the years. Starting in 1990, a comprehensive quality assurance protocol of 10% duplicates exposure, 5% spikes, and 5% blanks was followed. Prior to 1990, a similar but less comprehensive program was followed. The total instrumental variability of the ATDs is estimated to be approximately 14% over the 17-year monitoring period based on the variability of the track material calibration and reader's historical reproducibility.

Housing, climate, and weather

During the survey, homeowners were asked to report any changes in their home's structure, occupants, and heating-ventilation–air conditioning (HVAC) systems. In 1986, 1996, and 2000 homeowners filled out questionnaires about their home and its use. The influence of weather variations on radon was investigated using two different data sets. In 1996, a preliminary study looked at the 1983-1995 year-to-year radon changes and local weather variables from the U.S. National Climate Data Center. Contour maps of temperature, precipitation, and heating degree-days for each month at each site were generated through kriging. The annual average of the local weather variable extracted from the contour maps were compared through regression analysis to see which variables were useful in predicting the indoor radon concentrations. A final analysis of the radon variation of the sites in the full data set (1983-2000) used county average climate data from NOAA, aggregated by the LBNL high radon project, for annual averages (LBNL 2006).

Analytical methods

Radon concentrations and their log-transformed values were tested for spatial (site-to-site) and temporal (year-to-year) variations. The distribution shape was evaluated for normality using the Shapiro-Wilks test at the 5% probability level. Linear regression and visual inspection were used to test the year-to-year radon changes for systematic trends or abrupt changes at each site. The temporal variation was parameterized as the ratio of the standard deviation of the yearly radon measurements at the site divided by the mean, and is referred to as the site's coefficient of variation (COV). A number of likely probability distributions were fit to the COV distribution across sites to identify its shape. The best COV distribution was selected based on the chi-square test. Pearson correlation coefficients and multiple linear regressions were used to investigate the effects of continuous variables, like precipitation on the COV. Wicoxon rank sum test was used to test differences in subsamples of the log transformed COV. For discrete housing changes, like adding air conditioning, the significance of the effect was assessed with Wicoxon test on the pre- and post-change radon averages. Housing and climate factor influence on the house-averaged COV were tested using mixed general linear regression models.

RESULTS

Houses and their environment

Most houses were located on flat land where the water table was deeper than the basement floor. Most houses had basements that were 50 to 80% below ground level, had concrete block walls and poured concrete floors without a sump. Half of the houses had one level above the basement while thirty-five percent had two levels above the basement. Only four houses (5%) were one-story houses without basements. Not all sites produced data suitable for inclusion in the analysis. To be included, a site had to have a total of three or more annual average measurements. Houses were lost when participants moved, died, or stopped returning detectors. Three houses installed active mitigation systems after the start of the study. Only the pre-mitigation measurements from two of those houses are included in the final analysis. One hundred and ninety-six sites in 98 houses were included in the final analysis. The sites included 94 basement rooms, 99 first floor rooms, and three second floor rooms. Ninety–six percent of these sites were regularly occupied (10 or more person-hours per week).

Eighty-four homeowners completed forms that reported any changes to their homes during the survey. Only three homes had no significant changes during the entire period. In 1990, the age of the houses ranged from 5 to 103 years with a median age of 24 years. Several seasons during the study period showed significant variation from climatic norms in the region (NOAA 2006). Three years; 1993, 1996, and 1997, were cooler than average by more than one standard deviation; 1996 and 1997 had cold winters while 1992 and 1993 had cold summers. Three years, 1998, 1999, 2000 were significantly warmer; 1998 had a warm summer and winter while the other years had warmer winters. Snowfall in 1996 was significantly above average while 1993 and 1999 were rainier than average. Since the radon measurement year ran from October to October a "radon measurement year" includes the winter of that year and the summer of the next year. Minnesota's climate encourages houses with low ventilation rates and good thermal insulation. House heating loads varied from 7,000 to 12,000 degree-days and cooling loads from 150 to 900 degree-days (Base 65^0F). Most houses were heated with a forced air by a furnace located in the basement. About 30% of the houses had air conditioning in 1990 and approximately 30 % more added air conditioning before the end of the survey.

Radon concentrations

Most sites in this study have one or more year-long measurements in the early 1980's and continuous year-long measurements from 1990 to 1999. In addition, 43 houses had a short-tern screening measurement as part of the EPA state surveys (Steck 1990). The year-long measurements span a range from 4 to 19 years, with a median of 13 years. The number of radon measurements per site ranged from 3 to 19, with a median of 10. One home has continuous measurements that cover all but one year its history. A total of 1700 year-long radon measurements were made at the 196 sites. The log-transformed radon distribution across all sites passed a Kolmogorov-Smirnov test but had a $p<0.05$ for the Shapiro-Wilks test. However, when separated by level, all log-transformed distributions passed both normality tests. The geometric mean radon at all sites in all years was 120 Bq m^{-3}, with a geometric standard deviation of 2.0. Within a house, the radon concentration varied by floor with a mean of 150 Bq m^{-3} in basements and 100 Bq m^{-3} in first floor rooms. The ratio of the first floor to the basement radon concentration was normally distributed with a mean of 0.65 and standard deviation of 0.16. Other radon distribution statistics are given in Table 1.

Table 1. Long-term average radon concentrations at sample sites

	Number	GM[a] Bq m^{-3}	GSD[b]	Average Bq m^{-3}
All sites	196[c]	120	2.0	150
Basement	94	150	1.9	190
First floor	99	100	1.9	120

[a] Geometric mean [b] Geometric standard deviation [c] Includes 3 second floor sites

Year-to-year radon variation at all sites

The median COV for all sites is 26% with a geometric standard deviation of 1.5 and an average of 28%. Table 2 shows the distribution statistics by floor. If we assume that the instrumental uncertainty adds in quadrature to the true variation, the adjusted COV statistics for the true variation would be 22% and 24% respectively.

Table 2. Year-to-year coefficient of variation at sample sites

	Number	GM[a] %	GSD[b]	Average %	95% CI
All sites	196 [c]	26	1.5	28	24 – 27
Basement	94	26	1.6	27	23 – 28
First floor	99	27	1.5	29	24 – 28

[a] Geometric mean [b] Geometric standard deviation [c] Includes 3 second floor sites

DISCUSSION

Previous study

No studies have measured the year-long average radon in a large, random sample of US homes in a variety of climatic conditions and tracked the variations in the average over a decade or more. There are a few reports of the year-to-year variations in the annual average indoor radon concentrations in a small sample of homes for a few years. Martz et al. measured radon in 40 single family dwellings in and near Grand Junction Colorado for six years (Martz et al., 1991). The sites included basement and first floor rooms. In the 25 sites where a valid measurement was made each year and no major change was made to the home, the mean annual average radon COV was 25%. When the detector's response was factored out, the mean COV was reduced to 22%. The COV was similar at the other sites with shorter temporal coverage.

Temporal radon trends

The median radon at all the sites changed little from year-to-year. The year-to-year COV of the group mean was only 14%. Figure 2 shows the year-to-year variation in a three houses whose COVs were near the median value (~25%).

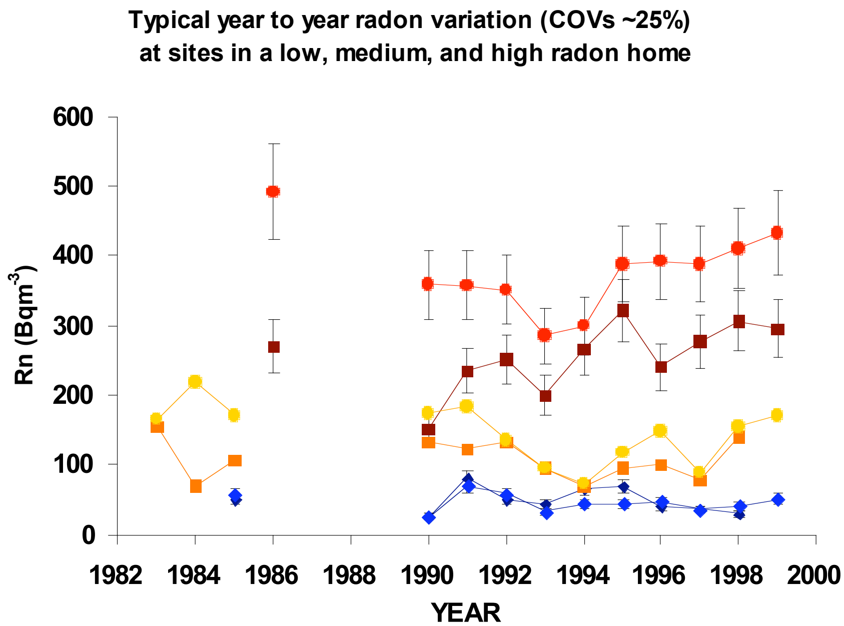

Figure 2 Sample year-to-year radon changes in houses without persistent trends and median COVs.

Several individual sites did show significantly larger temporal changes. When individual sites were analyzed for year-to-year variation both the radon and log-transformed annual average distributions passed the normality test at about the same rate (~90%). Those houses that failed the normality test were further analyzed to look for a progressive temporal trend or a persistent change initiated by a house or lifestyle changes. A visual review showed coordination between some building and radon changes but not others. Significant correlation between radon and measurement year was observed for both radon and log-transformed radon at 23 of the 196 sites. Linear regression and visual inspection

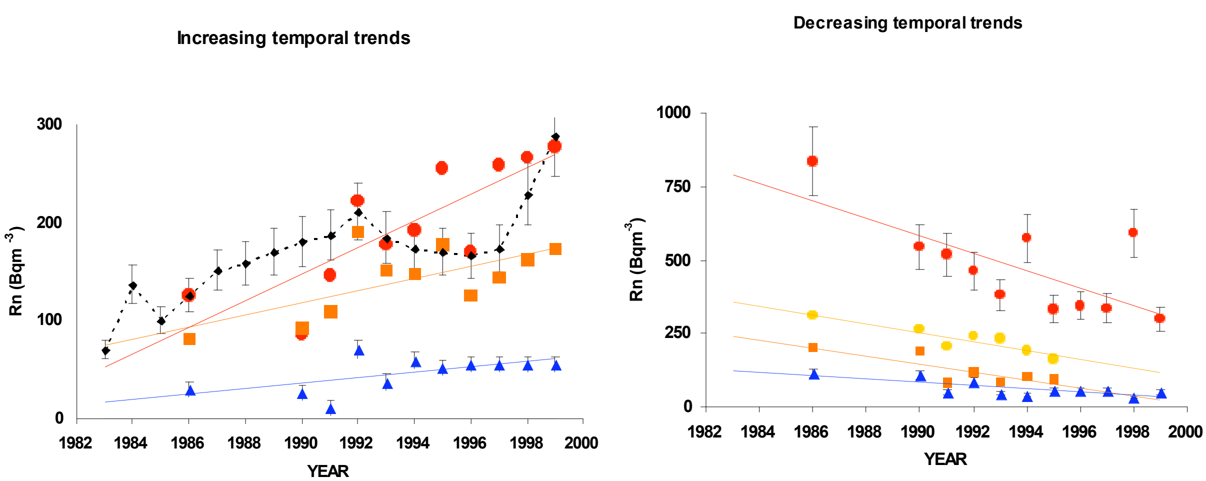

Figure 3 Sites with persistent temporal trends

suggests that persistent increasing trends were present at 13 sites and decreasing trends at 10 sites. Examples are shown in Figure 3.

Factors that affect year-to-year variation

The radon variation in these houses does not include changes associated with new principle occupants, since at least one adult occupant was a consistent resident throughout this study. The radon variation does not depend on the age of the house. The COV does not depend strongly on the radon concentration. It is 28% for radon below 150 Bq m^{-3} and 23% for sites with radon above 150 Bq m^{-3}

During the study period there were significant periods of climatic deviations. A preliminary study of the effects of weather on radon concentrations, found that the only annual precipitation showed significant correlation over the 10 years studied. However, precipitation explained less than 10% of the year-to-year radon changes. In the final analysis of the effects of climate on radon COV, the average hours of snow influenced the log-transformed COV significantly. Houses sited in snowier climates tend to have higher radon variation.

Correlations between the COVs and numerous house characteristics including the house's age, local environment, climate, number and type of floors, heating-cooling system, and structural components were investigated. Those factors that showed significant correlations were included in a general linear regression analysis. Factors that correlated but were not significant for the COVs included house age, measurement floor, number of floors in the house, heating-cooling system type, fuel type, and ventilation fans. Houses that were exposed to winds, particularly the prevailing winds from the north and west showed significantly higher COV's.

The radon history was reviewed at each site in the 80 houses that reported some modification that might influence radon. HVAC systems, windows, and insulation were the most frequently changed components. Winter window coverings, house structure, air-conditioning, and heating systems seemed to lead to radon changes of 50% at some individual sites in the year following the change. The pre- and post-change radon averages were tested using a paired sample t-test to see which factors consistently caused significant radon changes. Heating-ventilation system changes, expanding basements, and major structural additions consistently caused significant radon changes. Changes to winter window covering, and air-conditioning did not consistently cause significant radon changes across sites but often made significant changes in individual homes. In individual cases, house modification made large radon changes. Figure 4 shows two examples.

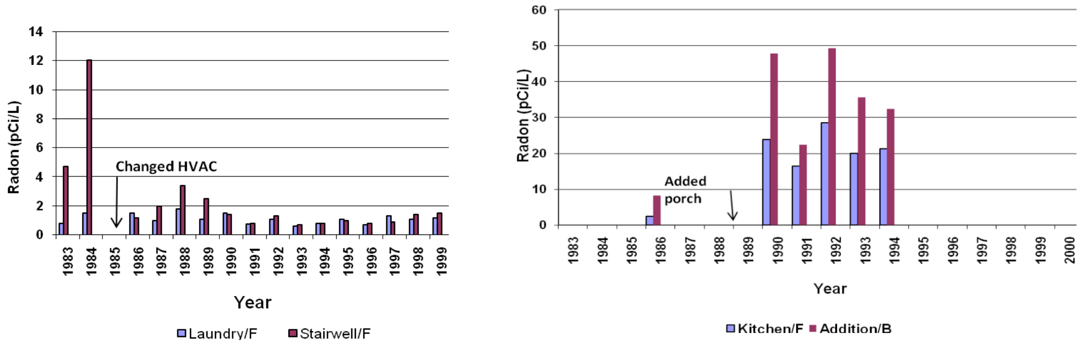

Figure 4 Examples of large radon changes created by house modifications

Implications for house tests and epidemiology

The radon-related risk in homes is often estimated from a single radon measurement that covers less than one year. Test results are often used as a diagnostic tool to judge the home's contamination status using some radon reference or action level. Normally the performance of these diagnostic tests is judged using year-long measurements as the gold standard. The present data set allows a comparison of both short term and year-long measurements to a better gold standard; multi-year average radon. The diagnostic and predictive performance of screening tests and year-long measurements was compared to the "true concentration", the multi-year average radon concentration in the living spaces. This living space average was weighted for mobility by assuming 7% of the time was spent in a basement (Field et al. 1998). The US action level, 150 Bq m^{-3}, was used as the reference level. The median of the mobility-weighted, multi-year living space radon in this subset of the houses was 110 Bq m-3. Twenty-eight percent of the houses had true concentrations above the reference level. In 1988, short-term (2 day) radon screening tests were made by the Minnesota Department of Health in 43 of the houses as part of the U.S. EPA's State Residential Radon Survey in Minnesota (Steck 1990). To minimize any bias from persistent or abrupt temporal radon changes in comparing the short-term and long-term home testing methods, the 1990 first floor ATD measurement were used as the prototype ATD test result. The correlation coefficient of the gold standard with the screening tests (basement) was 0.25 (R^2) while it was 0.95 for a year-long ATD measurement on the first floor. So if it is used in a non-threshold approach, a year-long ATD test was superior to a screening test. The ratio of the ATD test result to the true concentration had a median value of 0.96 with a 95% confidence interval from 0.86 to 1.02. The median for the short-term screening tests was 1.24 with a wide confidence interval from 1.19 to 1.72. When used to test against a threshold, year-long ATD tests outperformed 2-day screening tests. A single screening test correctly classified the true living space radon 79% of the time. The predictive value of a positive test screen was 58% and a negative screen was 96%. Note that the predictive value of a radon-independent test would be 50%. The good predictive value of a negative screen is understandable since the gold standard only included 7% of the basement radon concentration and the first floor generally have much lower radon than the basement. The ATD test had a more balanced diagnostic performance. It had a correct classification rate of 84%, positive test predictive value of 70% and a negative test predictive value of 90%.

The predictive performance improvement of longer tests is in general agreement with the comparative test performances seen in another study in Minnesota houses (Steck 2005).

Studies of residential radon and lung cancer face a number of challenges including the need to accurately reconstruct radon progeny exposure over long periods (Steck and Field 2006). Most of the studies that have been included in recent pooling studies (Krewski et al. 2005, 2006 Darby et al. 2005) use one or more year-long contemporary radon gas measurements as a surrogate for risk. If past radon concentrations are significantly different from present concentrations, then a systematic bias may be introduced in the risk coefficients. If radon varies wildly from year-to-year, then the variation will have a tendency to obscure the risk. Significant misclassification due to year-to-year variation was seen in a preliminary Monte Carlo analysis of three central North American studies included in the North American pooling (Steck 2002). Recent work on regression calibrations show that the variation, if known, can be used to address this retrospective measurement error (Darby et al. 2005 Fern et al. 2006). Factors that influence the year-to-year variation may be used to improve regression calibrations for houses that show high variation or to identify homes that need retrospective radon measurements. Our results suggest that special attention or adjustment may be warranted when changes are made in a home's substructure, HVAC, or when the house is located in snowy, windy environment.

CONCLUSIONS

Indoor radon concentrations can vary considerably from year–to-year even in homes where the occupants remain the same. Most of the yearly variations in these Minnesota homes ranged from 24% to 27% and showed no persistent temporal trend. Climate, environment, house modification and instrumental factors contribute to the variation. Some houses showed dramatically larger radon changes when the structure or HVAC systems are modified. The magnitude and causes of the radon variation should help interpret and adjust the results of radon-lung cancer studies that were done in nearby regions. In this radon-prone area, a year-long ATD measurement provided better risk assessment and diagnostic test than a 2-day screening measurement.

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