RESIDENTIAL RADON RISK ASSESSMENT: HOW WELL IS IT WORKING IN A HIGH RADON REGION?

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ABSTRACT

Three surveys of long-term indoor radon concentrations in Minnesota living spaces show that the state has many homes with elevated radon. A large random sample of Minnesota homes had a geometric mean of 3.5 pCi/L. Forty two percent had radon concentrations above 4pCi/L. A comparative study of short term and long term radon measurements in a subsample of these homes show poor correlation between short-term and long-term indoor radon concentrations as a result of significant temporal variation over the different measurement intervals. This poor correlation yields a significant failure rate when the current diagnostic testing protocol is used to select an appropriate action. When measurement errors are combined with some homeowner's failure to follow the mitigation decision protocol, the current radon assessment procedure fails in many homes.

INTRODUCTION

Chronic exposure to elevated radon (^{222}Rn) decay product concentrations is recognized as health risk (NRC 1999, UNSCEAR 2000). The annual average radon concentration in the living space (AALS) is currently considered the "gold standard" for estimating that health risk. The US E.P.A. has established and disseminated standard procedures for homeowners to use when assessing their potential residential radon exposure (US EPA 2004). The radon-related radiation dose that an individual receives varies considerably because radon concentrations have large temporal and spatial variability. Multiple factors influence the spatial and temporal variability of indoor radon. These factors make it difficult to create a measurement and decision making protocol that is accurate, efficient, and widely applicable. While the radon-related risk is associated with chronic exposure, the human desire to want an immediate answer introduces a tension in the measurement process that often results in risk assessment that is based on highly uncertain results. This effect may not be appreciated by all stakeholders. Although long-term measurements (LT: 90 days or more) are listed as an option, anecdotal data suggests that the overwhelming majority of people use short-term tests (ST: 2 to 7 days) to make a decision about radon reduction action.

The Citizen's Guide recognizes the temporal variation (US EPA 2004). It cautions that short-term measurements may not be accurate. The implication of this caution may not be clear to homeowners and no guidance is given about the success or failure rates of short-term tests to predict AALS. The decision protocol that uses those uncertain measurements needs to recognize the limitations introduced by spatial and temporal radon variation. Regional differences in the underlying radon distribution in homes can strongly affect the efficacy of the decision-making process. That is, a measurement-decision protocol's performance may be quite different in a region where most homes have low radon (~1pCi/L) than in a region where the average home may have concentrations near the present action threshold (4pCi/L). One possible modification to the protocol might incorporate the regional radon potential in formulating the decision-making guidelines.

In this work, we examine the impact of temporal variations on radon measurements and their interpretation by homeowners in a region where elevated radon is widespread. Measurements from three separate surveys will be used to illustrate that:

1. indoor radon concentrations are elevated across Minnesota with western and southern regions having the highest concentrations;
2. the measurement interval has a significant effect on the precision of the measurement. Longer-term temporal variations are about roughly equivalent to instrumental variation;
3. the response of homeowners following a "typical" radon assessment frequently leads to inappropriate inaction, in part due to the failure of the diagnostic test as a result of temporal and spatial radon variation.

METHODS

Surveys

1. **Map survey:** We collected a long-term radon measurement from the lowest lived-in level of randomly-selected Minnesota homes to estimate the median radon by zip code.
2. **Temporal survey:** We tracked the temporal radon variation on a daily, monthly, and seasonal basis for one year in randomly recruited western and southern Minnesota homes.
3. **Follow-up survey:** Following a telephone interview, short and long term radon measurements were made in eastern Minnesota homes to compare past and present concentrations in homes and to track homeowner actions based on their radon results.

Radon measurement devices

Average radon concentrations for periods ranging from one month to one year were measured using alpha track detectors (ATDs). Two models of detectors were used in the map and temporal surveys. RADTRAK© ATDs, from Landauer Inc. (Glenwood, Illinois), and ATDs from our laboratory, labeled the Minnesota Radon Project (MRP), were used to measure the integrated radon concentrations. The MRP ATDs detectors are routinely calibrated and tested at national laboratories, often as part of organizational intercomparison exercises [Steck et al. 2002, 2004]. For the past 15 years, these ATDs have showed a consistent instrumental coefficient of variation (COV) of 14% for exposures near the low range of these measurements (1 kBq m^{-3} d) and 12%

for measurements in the higher range (50 kBq m^{-3}d). Side-by-side exposures of the RADTRAK© and MRP detectors in both chamber and residential setting are routinely conducted to insure consistent results. An adjustment was needed to combine the results during only one year (2002) when the two models exceeded the difference expected from their individual instrumental uncertainties. Only RADTRAK© ATDs were used in the Follow-up survey.

Commercial charcoal canisters (CCs) were used to measure the short-term average radon concentrations in each season. The detectors used where from two independent laboratories. One model (AE) was used for two and three day exposure period and the other model (AC) was used for a four-day exposure. The detectors were then returned to the manufacturers' laboratory for analysis. These charcoal canisters meet with current EPA standards to measure indoor radon levels.

The quality of the detectors performance was monitored by using 3% of the installed detectors blanks, 5% spiked, and 8% side-by-side duplicates. None of the unexposed (blank) short-term charcoal canisters or the long-term alpha track detectors indicated radon concentrations above their lower level of detection of 10 Bq m^{-3} and 8 Bq m^{-3} respectively for their minimum exposure times. Laboratory samples exposed to known concentrations showed a 10% bias between the two types of short-term detectors and the alpha track detectors when exposed side-by-side at high radon concentrations. The average reproducibility from side by side exposure was 20% for the two-day charcoal canister model AE and 15% for the four day charcoal canister model AC. The month-long alpha track detectors showed an 8% variation at 4pCi/L and 11% variation at 1 pCi/L.

Spatial and temporal distributions were tested for normality and appropriate parameter statistics were calculated.

All the measurements were conducted in lived-in spaces, where we use a standard of occupation by a person for 10 or more hours per week to categorize lived-in spaces.

Map survey: radon in living spaces of Minnesota houses

Participants in this survey are randomly selected from a telephone number database in selected zip codes from across the state. The zip codes are selected primarily to accurately map the spatial variation of indoor radon across the state and to cover areas of high population density. Each house receives one ATD by mail for a 90 day measurement in the lowest lived in level.

Temporal survey: temporal variation of radon in a high radon region of Minnesota

Eighty-five homeowners were randomly solicited to participate in this study from a pool of 150 alumni who lived in western and southern Minnesota and had agreed to participate in the Map survey described above. Radon measurement devices were mailed to the homeowners during the period from September 2002 to October 2003 for immediate placement at two locations in their home. The primary location was selected to be in the lowest living level where someone spent 10 or more hours per week. Short-term, month-long and year-long radon measurements were taken at this location. Homeowners were instructed to expose the two day and four day CC detectors side-by-side. An additional year long measurement was taken at a secondary location, usually a bedroom in a higher level of the home.

Spatial and temporal distributions were tested for normality and appropriate parameter statistics were calculated. The accuracy of shorter term measurements to predict the annual average radon (AA) was calculated for comparison from the average percentage difference of the short-term measurement from the annual average at that site. This percentage difference was corrected for the instrumental uncertainty of the type of detector used for the short term measurement. The utility of short-term measurements to predict annual average radon in the living spaces was evaluated through the sensitivity, specificity, efficiency, and predictive value statistics (Mackinnon, 2000).

Follow up survey: Actions and measurements following an initial short-tem measurement
Addresses and radon screening measurement results were obtained from Minnesota county health departments. Missing phone numbers for those addresses were extracted from a database (DeLorme Street Atlas Phone 2004) when possible. The remaining list was reduced to include only those that appeared to be a house address and that had a homeowner-made screening measurement result between 0.5 and 100 pCi/L that was taken 9 to 18 months earlier. Participants were called and asked to answer 15 questions about their radon measurement(s) and actions. After these preliminary questions, they were asked if they would be willing to measure their house for radon again. If they agreed (more than 80% did), we sent them a charcoal canister for a new 3 day screening test and two ATDs for 90 day tests at the screening site and at another location, preferably a bedroom on another floor.

RESULTS

Map survey
This survey is still in progress, so these results are not final. To date, 2121 houses have been measured. Forty–two percent (42%) of the living spaces have long-term radon concentration that were 4pCi/L or higher. The distribution of radon concentrations within the homes is given in Table 1. Measurements were made in the basement and the first floor at roughly the same rate. The median of the basement radon concentration distribution was slightly higher than first or second floor. Bedroom, recreation room, and den distributions tend to have higher radon than living room and kitchen distributions most likely reflecting the increased frequency of sampling those rooms when they are in the basement. However the distributions have large standard deviations, so the range of values strongly overlaps between floors and types of rooms.

Table 1. The distribution of indoor radon within Minnesota home living spaces[1]

Data Set	N	Mean pCi/L	GM[2] (GSD) pCi/L	95% CI[3] pCi/L
All	1257	5.0	3.5 (2.4)	1.5 - 8.3
Basement	534	6.3	4.9 (2.1)	2.3 -10.2
First Floor	499	3.8	2.7 (2.3)	1.2 - 6.2
Second & higher	11	4.8	3.7 (2.3)	1.6 - 8.4
Bedrooms	237	5.1	3.5 (2.4)	1.5 -8.4
Recreation rooms	252	5.6	4.1 (2.4)	1.7 - 9.6
Living rooms	187	3.8	2.7 (2.3)	1.2 - 6.3
Kitchen	90	3.5	2.6 (2.3)	1.1 - 6.0
Den	68	5.2	3.6 (2.4)	1.5 - 8.8

[1]A place where someone spends 10 or more hours per week. Taken in the lowest lived-in level of the home
[2] Geometric mean and geometric standard deviation; all distributions are lognormal
[3] 95% of the measurements fall in this range of values

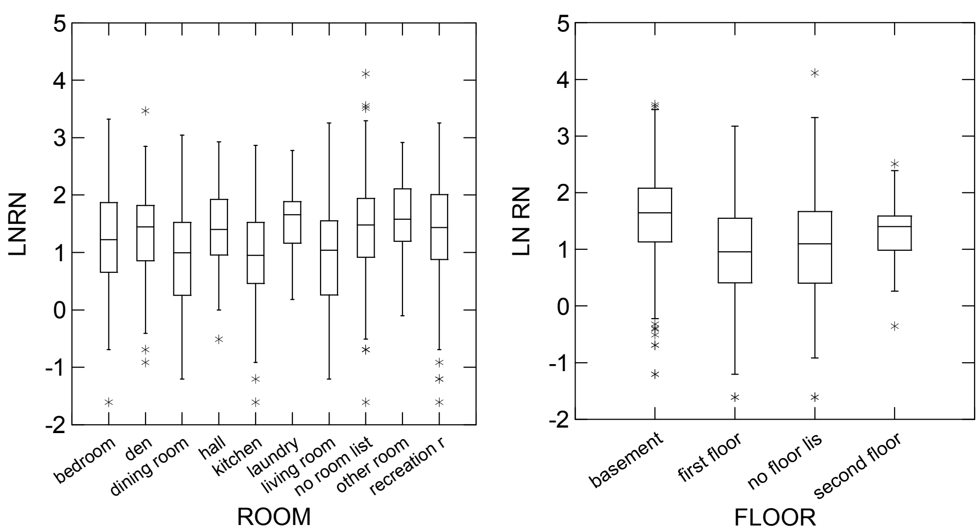


Figure 1 Distribution of radon by room (a) and floor (b) within Minnesota homes from the Map survey.

Temporal survey

Seventy-five homeowners were included in the final analysis because they completed at least one short term, six monthly and one annual average measurement (Steck et al. 2004). Seventy-percent (70%) of these houses had a living space whose annual average radon concentration was above the action level. Figure 2 shows a sample of the radon measurement results at one primary site in one house. Table 2 shows the radon measurement distribution parameters. Figure 3 shows the correlation between the short-term screening results and the AALS calculated from the average of the year long measurements at the primary and secondary sites.

Table 2. Summary of temporal survey results. All distributions are lognormal

Location and Type	Number	Geometric Mean[1] (SD)
Short term		
Primary site: 2 day	177	4.1 (3.0)
Primary site: 4 day	178	4.9 (2.3)
2 or 4 day	355	4.5 (2.6)
Primary site: 30d	767	4.9 (2.0)
Primary site: 90d in 2001	80	5.5 (2.2)
Annual average		
Primary site	75	5.1 (2.1)
Secondary site	72	3.8 (2.1)

[1] pCi/L

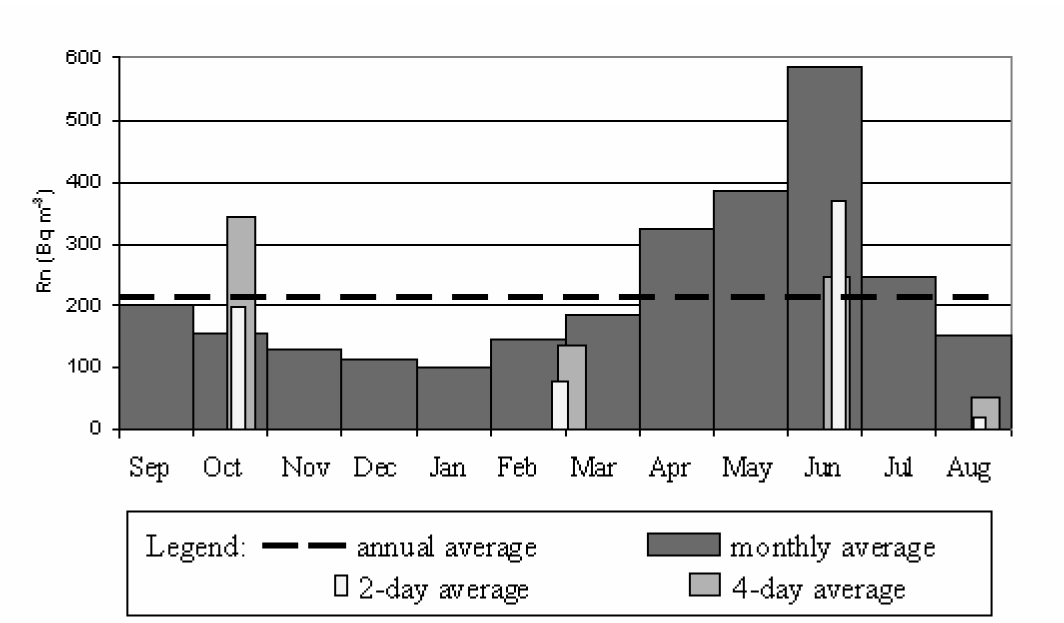


Figure 2. Sample Temporal survey results from measurement site SD3A0.

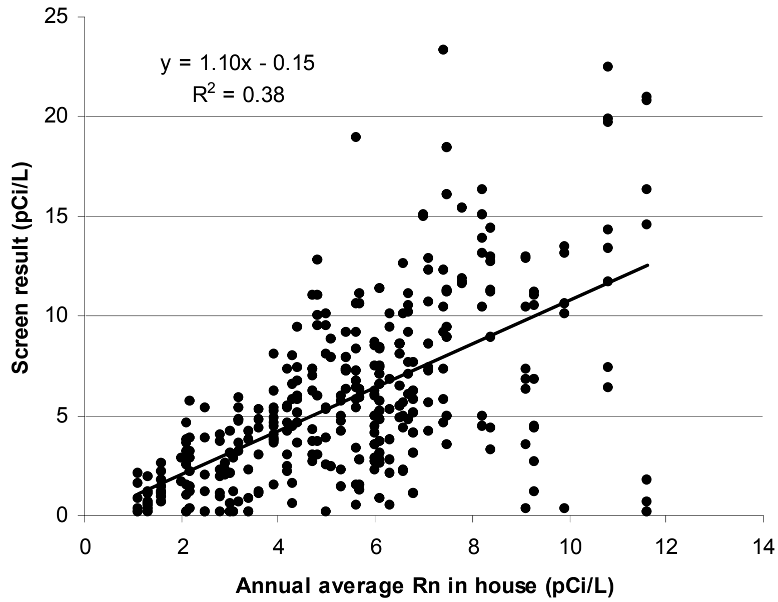


Figure 3. Linear regression between ST screening measurements and the annual average radon in the house (one high radon house is not shown) in the Temporal survey

The coefficient of variation (COV= SD/ Average) of the various temporal measurement intervals is shown in Table 3.The annual average radon at the measurement site was used as the "gold standard"

Table 3. Comparative variations of different averaging periods and operating conditions at the primary measurement site in the Temporal survey

Measurement Type: House conditions	**COV about the annual average[1]**
Two day: closed	76%
Four day: closed	70%
Monthly: normal	40%
Seasonal (90 day) average: normal	25%
Semi-annual average: normal	17%

[1] Corrected for instrumental variation

Follow up survey

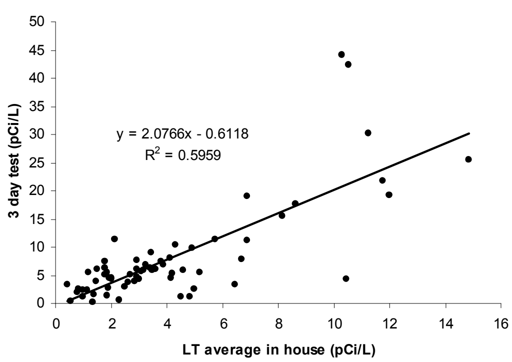
This survey is still in progress, so the results are preliminary. To date, 248 people completed a telephone interview and 104 houses have completed at least one contemporary short-term and one long term measurement. Eighteen of those homes have a mitigation system.

Interview responses

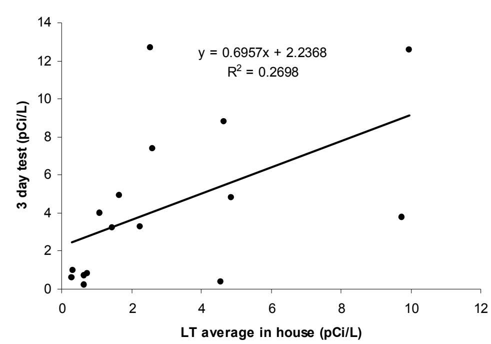
The overwhelming majority (84%) of respondents believed that radon was a serious health concern and 80% identified cancer or lung cancer as the disease associated with radon exposure. Media reports (32%), friends and family (21%), and health professionals (14%) were the primary motivating causes for making a measurement. Almost all (92%) the radon measurements that the homeowners made originally were short-term tests in the basement (93%). Most people (59%) did not take a second measurement. Since we did not have a complete radon measurement history for all individuals, we can only analyze the actions of those who did not take a second measurement. Two thirds of those single measurement homes had screening results less than 4 pCi/L, 20% had results in the range from 4 to 8 pCi/L, 5% had had results above 8pCi/L. A few homeowners (6%) mitigated their homes based on a single screening result. People have a better recollection of the general category of their screening results rather than a specific number so we asked them if they believed that there radon measurement results indicated that their house was safe or unsafe and if they had mitigated their home. Half reported that they believed their home to be safe and did not mitigate. Thirteen percent believed their home to be unsafe and installed a mitigation system. However, 27% believed that their home was unsafe but did not mitigate. Homeowners installed one third of the mitigation systems. Only 59% of the people who installed a mitigation system performed post-mitigation radon measurements. Almost all (90%) of those post-mitigation measurements were short-term.

Current radon measurements

In each house, one CC and one ATD were exposed at the primary measurement site, the same location that was used for the prior screening measurements. The primary site floor was usually the basement (80%) followed by the first floor (14%). The primary room measured was a bedroom (24%) with a recreation room (22%) being a close second. The second ATD was usually placed on the first floor (58%) in a bedroom (59%).



(a)



(b)

Figure 4. Correlation between a screening test and the long-term average radon in the house for (a) unmitigated and (b) mitigated houses.

A summary of the radon concentration distributions, grouped by mitigation status, is shown in Table 4. The correlation between the most recent short-term (ST) measurement and the long-term (LT) radon concentration averaged in each house is shown in Figure 4.

Table 4 Current radon concentrations in the Follow-up survey homes

	N	Current ST GM[1] (GSD)	Current ST %>=4pCi/L	LT living space average GM[1] (GSD)	LT living space %>=4 pCi/L
Unmitigated houses	86	5.1 (2.7)	71%	3.0 (2.2)	50%
Mitigated houses	18	2.4 (3.6)	44%	1.8 (2.8)	28%

[1] pCi/L

DISCUSSION

Most radon measurements in the US are made by homeowners using charcoal canister detectors. In a typical case, a single detector is exposed from two to four days under "closed" house conditions in the lowest living level of the home. This screening test is used as a diagnostic tool to decide what action, if any, to take to reduce radon exposure. Only if the result is 4 pCi/L (or above) is the homeowner directed to take action, namely a second screening test. If the average of those two tests are 4 pCi/L (or above), then the homeowner is urged to fix their home (U.S. EPA 2004). The technical basis and implications for this protocol are given in the Technical Support Document (U.S. EPA 1992). Two papers provide additional analysis and a summary of the measurements that were used to develop this decision-making protocol (White 1994, White et al. 1994). The Technical support document performs its analysis of the diagnostic test performance using national radon distribution parameter estimates. White and colleagues used a national measurement sample, roughly 50 to 70 houses per state in 11 to 21 states, from the State Residential Radon Survey (SRRS) data to assess the diagnostic performance of the EPA protocol.

In recognition of the spatial variation of indoor radon, the EPA has published a radon potential map at a county level with three zone categories. Region 1 is the zone of highest potential. The states sampled for the SRRS contained a good mixture of those zones. On the other hand, states in the Upper Midwest are dominated by zone 1 counties. In Minnesota, 80% of the population lives in a Zone 1 county. The results of our random sample Map survey generally support the Minnesota Zone map. Table 1 shows that the statewide average lowest-level living space has an median value of 3.5 pCi/L. Table 2 shows that the subset of participants from western and southern Minnesota (all Zone 1 counties) , included in the Temporal study, have a higher median radon concentration, 5.1 pCi/L. These results generally agree with earlier studies in Minnesota and Iowa that identified the Upper Midwest as a high radon region (Field et al. 2000, Steck, 1992, Steck et al. 1996).

The performance of any diagnostic test, like radon screening, depends on the precision of the measuring instrument and the underlying distribution. Previous comparisons of screening measurements in Minnesota suggested that the performance of the diagnostic protocol based on a single short term measurement had a combined failure rate of roughly 50% (Steck, 1990). White reports a similar failure rate for homes with radon concentration near the action level while the failure rate for homes with radon near the national average, the failure rate was less than 1% (White, 1994; Table 2). Although the current decision protocol recommends a second test if the first one exceeds the action level, many people base their action decision on a single detectors result. More than one third of the Follow-up survey participants who had initial measurement results above 4pCi/L stopped with a single screening measurement. When we conducted a new screening test in a subsample of the unmitigated Follow-up homes, 71% had screening results above the action level. About half of the unmitigated Follow-up houses proved to have long-term living space radon concentrations above 4 pCi/L.

Table 5. Classification performance indices of short term screening tests for predicting annual average Rn above 4 pCi/L at the primary measurement location and averaged across the house from the Temporal survey homes

Measurement	**Test performance indices**	
	In predicting the action status at the primary measurement location	**In predicting the action status averaged over the house**
Two day: closed house; Lowest lived in level	Efficiency[1] = 0.82 (CI: 0.75 - 0.87)	0.78 (CI: 0.71 - 0.84)
	(Efficiency of random test=0.55)	*(Efficiency of random test=0.54)*
	PV+ [2] = 0.97 (CI: 0.92 - 0.99)	0.88 (CI: 0.80 - 0.94)
	PV-[3] = 0.59 (CI: 0.46 - 0.70)	0.63 (CI: 0.50 - 0.75)
	Sensitivity[4] = 0.78 (CI: 0.70 - 0.85)[2]	0.79 (CI: 0.70 - 0.86)
	Specificity[5] = 0.93 (CI: 0.81 - 0.99)	0.76 (CI: 0.63 - 0.87)
Four day: closed house; Lowest lived in level	Efficiency = 0.77 (CI: 0.70 - 0.83)	0.79 (CI: 0.72 - 0.85)
	(Efficiency of random test=0.56)	*(Efficiency of random test=0.55)*
	PV+ = 0.95 (CI: 0.89 - 0.98)	0.90 (CI: 0.82 - 0.95)
	PV- = 0.49 (CI: 0.36 - 0.61)	0.61 (CI: 0.48 - 0.73)
	Sensitivity = 0.74 (CI: 0.66 - 0.81)	0.79 (CI: 0.70 - 0.86)
	Specificity = 0.87 (CI: 0.72 - 0.96)	0.79 (CI: 0.65 - 0.90)

[1] Efficiency = Correct classification rate; [2] 95%Confidence Interval; [3] PV+ = Predictive value of positive test: Probability that an observation with a positive test will be positive on the criterion. [4] PV- = Predictive value of negative test: Probability that an observation with a negative test will be negative on the criterion; [5] Specificity=proportion of true negatives classified as negative by the test; [6]Sensitivity=proportion of true positives classified as positive by the test

Tables 5 and 6 give various diagnostic performance indices for the Temporal and Follow-up survey populations. The efficiency, which is the correct classification rate, is similar to the earlier analyses that reported the combined incorrect classification rate as a performance index. The diagnostic test efficiency is higher for the Temporal homes than the Follow-up. Recall that the median radon of the Temporal homes is farther from the action level than the Follow-up home median. Hence, variations have to be higher in those homes for the test result to be on the other side of the action level from the true radon value. The efficiency of the diagnostic test in the Follow-up population is not much different from a random diagnostic test's efficiency. In addition, the low predictive value of a negative test means that those homeowners who believe, based on their single screening measurement, that they have a house below the action level are often mistaken.

An analysis using the more complete EPA protocol using sequential ST devices in some cases will be done when additional Follow-up survey data becomes available.

Table 6. Diagnostic classification performance indices for short term screening tests in the Follow-up survey in unmitigated homes.

	Test performance indices	
Measurement	**In predicting the action status at the primary measurement location**	**In predicting the action status averaged over the house**
Three day:	Efficiency[1] = 0.66 (0.53 - 0.77)[2]	0.54 (CI: 0.41 - 0.66)
closed house;	*(Efficiency of random test=0.48)*	*(Efficiency of random test=0.46)*
Lowest lived in	PV+[3] = 0.6 (0.4 - 0.7)	0.4 (CI: 0.3 - 0.6)
level	PV-[4] = 0.8 (0.6 – 1.0)	0.8 (CI: 0.5 - 0.9)
	Sensitivity[5] = 0.9 (0.7 – 1.0)	0.8 (CI: 0.6 - 0.9)[2]
	Specificity[6] = 0.5 (0.3 - 0.6)	0.4 (CI: 0.2 - 0.5)

[1] Efficiency = Correct classification rate; [2] 95%Confidence Interval; [3] PV+ = Predictive value of positive test: Probability that an observation with a positive test will be positive on the criterion. [4] PV- = Predictive value of negative test: Probability that an observation with a negative test will be negative on the criterion; [5] Specificity=proportion of true negatives classified as negative by the test; [6]Sensitivity=proportion of true positives classified as positive by the test

Figure 3 and 4 show that the correlation between a ST measurement and a LT measurement is weak. The variation of ST results about their LT counterparts is typically 70 to 80% (see Table 3). However, the instrumental variation, that is the variation devices show when exposed to constant radon concentrations, is typically less than 25%. This suggests that the variation shown in home exposures results from the natural variation of indoor radon over time. This presents a serious challenge to any protocol that is based on one ST measurement and even protocols based on two short-term measurements exposed sequentially in a short time period. Our analysis in the Temporal study population suggested that two ST measurements separated by at least a season were only marginally better than a single ST measurement. A reanalysis is planned that will combine the Temporal and final Follow up data sets.

Even if the radon concentrations in homes were constant and the measurement instruments were perfectly accurate, failures will occur. Our experience is that roughly 10 to 20% the ST devices fail, usually due to delays in the mail. About 30% of those who stopped with a single measurement should have decided to take a second measurement. In our remeasurement of the unmitigated Follow-up survey homes, half had long-term radon concentrations above the action level. Almost 70% of the people who believed that their home had unsafe levels of radon, decided not to mitigate. No post-mitigation measurements were done in one third of the mitigated homes. Almost one third (28%) of the mitigated houses currently have long-term radon concentrations above 4 pCi/L.

CONCLUSIONS

Minnesota is a high radon region where temporal indoor radon concentration variations due to climate, home construction, and lifestyle habits results in poor correlation between screening measurements and long-term radon concentrations. This poor correlation yields a significant failure rate when the current diagnostic testing protocol is used to select an appropriate action. When measurement errors are combined with some homeowner's failure to follow the mitigation decision protocol, the current radon assessment procedure fails in many homes.

ACKNOWLEDGMENTS

This work was made possible, in part, by grant number R01 CA85942-01A1 from the National Cancer Institute, National Institutes of Health and grants from the Minnesota Department of Health (MDH) through the SIRG program of the US EPA. This report is solely the responsibility of the author and does not necessarily reflect the official views of the NCI, NIH, MDH or EPA.

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