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RELATIONSHIP BETWEEN 2-DAY SCREENING MEASUREMENTS OF ^{222}Rn AND ANNUAL LIVING AREA AVERAGES IN BASEMENT AND NONBASEMENT HOUSES

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ABSTRACT

As part of an EPA/State cooperative program, a random sample of 41,648 houses from 30 of the 48 conterminous states have been screened for ^{222}Rn over the past four years. Charcoal canisters were placed in the lowest livable level and exposed for two days. In addition, 1-year alpha track detectors were used in a random subsample of houses with at least one detector placed on each livable level.

This paper describes the relationship between annual living area averages (ALAA) and wintertime, closed-house, 2-day screening measurements. Both 2-day and 1-year measurements of ^{222}Rn were made on 995 houses located in 13 states. A broad range of climates, geologic conditions, and housing types are represented in the sample. Equations for predicting ALAA are derived for screening measurements taken in the basement and on the first floor of nonbasement houses. These relationships are used to obtain predicted values of ALAA for the 41,648 houses for which screenings measurements are available. The distribution of predicted values of ALAA by house type are then characterized. To the extent that the 30 states represent the 48 conterminous states, these distributions apply to the nation as a whole.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

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INTRODUCTION

Short-term screening tests for ^{222}Rn are used to determine if additional testing (usually one year duration) is needed to more accurately characterize health risks to Rn exposure. The extent to which screening tests can properly identify houses needing further testing is governed by the degree to which short- and long-term measurements are related. This relationship has not been studied extensively. In a review of the published literature, Ronca-Battista (1) found only nine studies in which this issue was addressed and most of these had sample sizes less than 100 houses. This study attempts to provide a better understanding of this relationship.

A component of the EPA/State Indoor Radon Surveys involves two types of ^{222}Rn measurement devices in a subsample of houses. Each participating house is tested with a 2-day charcoal canister placed in the lowest livable level and 1-year alpha track detectors (ATDs) placed on each livable level. The 2-day test is carried out in the winter season under closed-house conditions. A total of 995 houses provided data for establishing the relationship between 2-day measurements and 1-year measurements.

OBJECTIVES

The purposes of this study were (1) to examine the overall relationship between 2-day screening measurements and annual living area averages (ALAA), (2) to determine if a screening measurement can be effectively used to predict the ALAA for an individual house, and (3) to examine the distribution of predicted values of ALAA for some 40,000 randomly selected houses for which screening measurements are available.

METHODOLOGY

Two indoor radon measurements (X, ALAA) were obtained from houses covering a 13-state area.[1] X is the 2-day charcoal canister measurement observed in a given house and ALAA is the annual living area average obtained by averaging all ATD readings taken on that house. In multiple level houses, a single ATD was placed on each livable level with a maximum of four ATDs per house. Two ATDs were used in one-story nonbasement houses. Averaging measurements from each level is one of several ways of characterizing the annual concentration in a house. Other ways include

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[1] States providing both short-term and long-term measurements include: Alaska, Arizona, Indiana, Iowa, Maine, Massachusetts, Minnesota, Missouri, North Dakota, Ohio, Tennessee, Vermont, and West Virginia.

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using only the first floor ATD measurement or using a weighted average of the ATD measurements from each level, where the weights reflect the proportion of time spent on each level.

This report examines the relationship between X and ALAA in basement and nonbasement houses. Values of X and ALAA for a given house are considered usable in the analysis if 1) the canister floor code matched the lowest floor code of the ATDS, 2) the ATDS used in calculating the ALAA had been exposed between 305 days and 425 days, 3) the canister was exposed within 30 days of the beginning of the ATD exposure period, and 4) a valid ATD reading was reported for each ATD originally placed in the house. A total of 997 houses provided data that met these requirements. After examining the data, two houses were excluded as outliers (one in Massachusetts and one in Tennessee). The relationships reported herein are consequently based on 995 houses--609 basement houses and 386 nonbasement houses.

A scatter plot of the data shows that ALAA is linearly related to X and that the variation in ALAA tends to increase as X increases. A relationship between X and ALAA is derived using a model which reflects these visual observations in the data. A specification of the model is given below.

The results in this paper employ a mathematical model that assumes that long-term measurements of ^{222}Rn are linearly related to short-term measurements and have variances that are proportional to their expected values. That is,

$$ALAA_i = (\alpha + \beta X_i) + \sigma Z_i(\alpha + \beta X_i)^{1/2} \tag{1}$$

where

$ALAA_i$ = annual living area average calculated for the i^{th} house,

X_i = canister measurement on the i^{th} house,

α, β, σ = parameters to be estimated, and

Z_i = random error for i^{th} house, assumed to be normally distributed with mean 0 and variance 1.

In order to convert (1) to a model having a homogeneous error structure, we divide by $(\alpha + \beta X_i)^{1/2}$ and substitute $\sqrt{ALAA_i}$ for $(\alpha + \beta X_i)^{1/2}$ on the left hand side of (1):

$$\sqrt{ALAA_i} = (\alpha + \beta X_i)^{1/2} + \sigma Z_i \tag{2}$$

The parameters in (2) were estimated using nonlinear least squares. The prediction equation $\sqrt{\widehat{ALAA}} = (\hat{\alpha} + \hat{\beta}X)^{1/2}$ was squared to obtain predictions of long-term concentrations for given short-term measurements. Similarly, endpoints of the 95% confidence interval for $\sqrt{\widehat{ALAA}}$ were squared to obtain a corresponding interval estimate for the long-term concentration.

RESULTS

SHORT- VS LONG-TERM RELATIONSHIP

Results of fitting equation (2) to data from basement houses and from nonbasement houses are given in Table 1. For each type of house, Table 1 gives the sample size, the prediction equation, the correlation between X and ALAA, and the standard deviation, $\hat{\sigma}$, from the fitted model. The prediction equations are

TABLE 1. EQUATIONS FOR PREDICTING ANNUAL LIVING AREA AVERAGES FOR BASEMENT AND NONBASEMENT HOUSES

Type of House	Sample Size	Prediction Equation	Correlation (X, ALAA)	Residual Error ($\hat{\sigma}$)
Basement	609	$\widehat{ALAA} = 0.69 + 0.54X$ (0.08)* (0.02)	0.82	0.51
Nonbasement	386	$\widehat{ALAA} = 0.53 + 0.61X$ (0.04) (0.02)	0.90	0.34

* (Standard error of parameter estimate.)

Basement House: $\widehat{ALAA} = 0.69 + 0.54X$ (3)

Nonbasement House: $\widehat{ALAA} = 0.53 + 0.61X$ (4)

where $\widehat{ALAA}$ is the expected (or predicted) value of the annual living area average in a house that has a screening measurement of X on the lowest livable level. The prediction equation for nonbasement houses reflect the exclusion of two (X, ALAA) data points considered to be suspect - (24.0, 2.2) and (39.6, 3.6). If these data points are included the prediction equation becomes $\widehat{ALAA} = 0.61 + 0.52X$.

Scatter plots of the data for basement and nonbasement houses are shown in Figures 1 and 2, respectively. Note that as the canister measurements get larger the ALAA measurements show greater dispersion. As noted previously, this increase in variability in long-term measurements is taken into account by the model used in the data analysis. Superimposed on each scatter plot are three lines. The center line is the prediction equation. The other two lines (designated as UCL and LCL) represent the estimated upper and lower 95 percent confidence limits on the predicted value for an individual house. The interpretation of the confidence limits in Figures 1 and 2 is as follows: if a 2-day canister reading is X for a given house, there is a 95 percent chance that the true ALAA for that house would be covered by the interval falling between the upper and lower lines corresponding to X. For instance, for a basement canister measurement of X = 10 pCi/L, we can be 95 percent confident that the interval (2.2-12.0) will cover the true ALAA for that house. The vertical spread in the data for a given value of X (as reflected by the distance between the upper and lower confidence limits) indicates that the ALAA varies widely among houses having the same canister measurement.

FALSE POSITIVE/NEGATIVE ERRORS

EPA currently recommends additional testing if the screening measurement exceeds 4 pCi/L. Furthermore, EPA recommends mitigation if a 1-year test exceeds 4 pCi/L. In this case, a perfect screening test would correctly classify a house as to whether its annual concentration would exceed 4 pCi/L. Although there is no perfect test, one can, however, assess the performance of a screening test by characterizing the probability of an incorrect decision. One of two incorrect decisions can be made on the basis of a screening measurement--if a screening measurement is ≤4 pCi/L, one may incorrectly conclude that the house annual concentration is ≤4 (false negative); if a screening measurement exceeds 4 pCi/L, one may incorrectly conclude that the house annual concentration is also greater than 4 pCi/L (false positive).

The probability that the ALAA will exceed 4 pCi/L, given a specified screening measurement, X, is given by

$$P\left[Z < \frac{(a + bX)^{1/2} - 2}{\hat{\sigma}} \,\middle|\, X\right] \qquad (5)$$

where Z is a standard normal deviate, a and b are the estimated model parameters, and $\hat{\sigma}$ is the standard deviation from the fitted model. This probability was calculated for screening measurements, X, ranging from 1 to 16 pCi/L for basement and nonbasement houses by substituting the appropriate parameter estimates from Table 1 into equation (5); the results are shown in Figure 3. The regions of false positive and false negative errors are noted and the probability of an error associated with a given screening measurement can be determined directly from the plotted curves.

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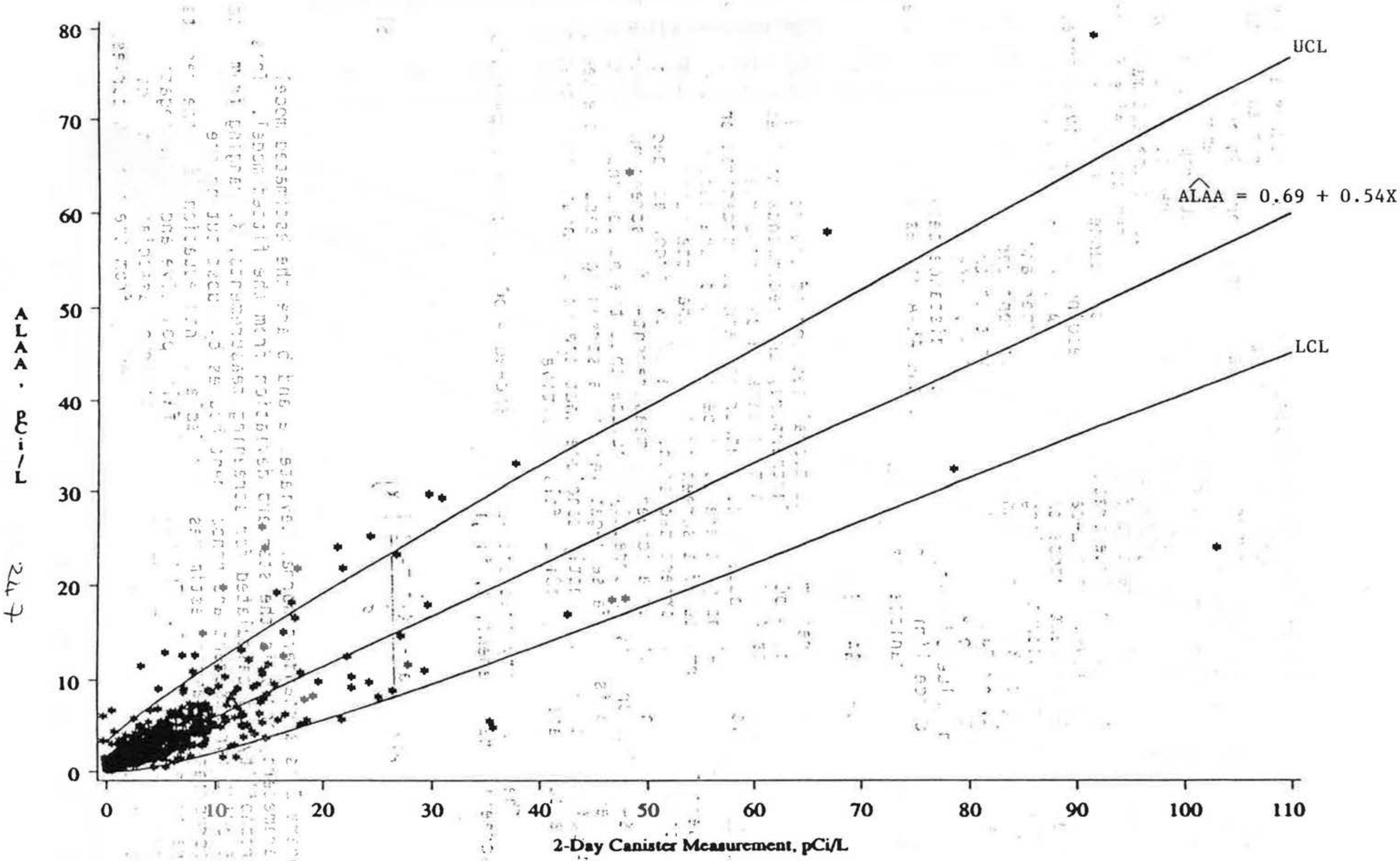

Figure 1. Relationship Between 2-Day Charcoal Canister Measurement And Annual Living Area Average - Basement Houses

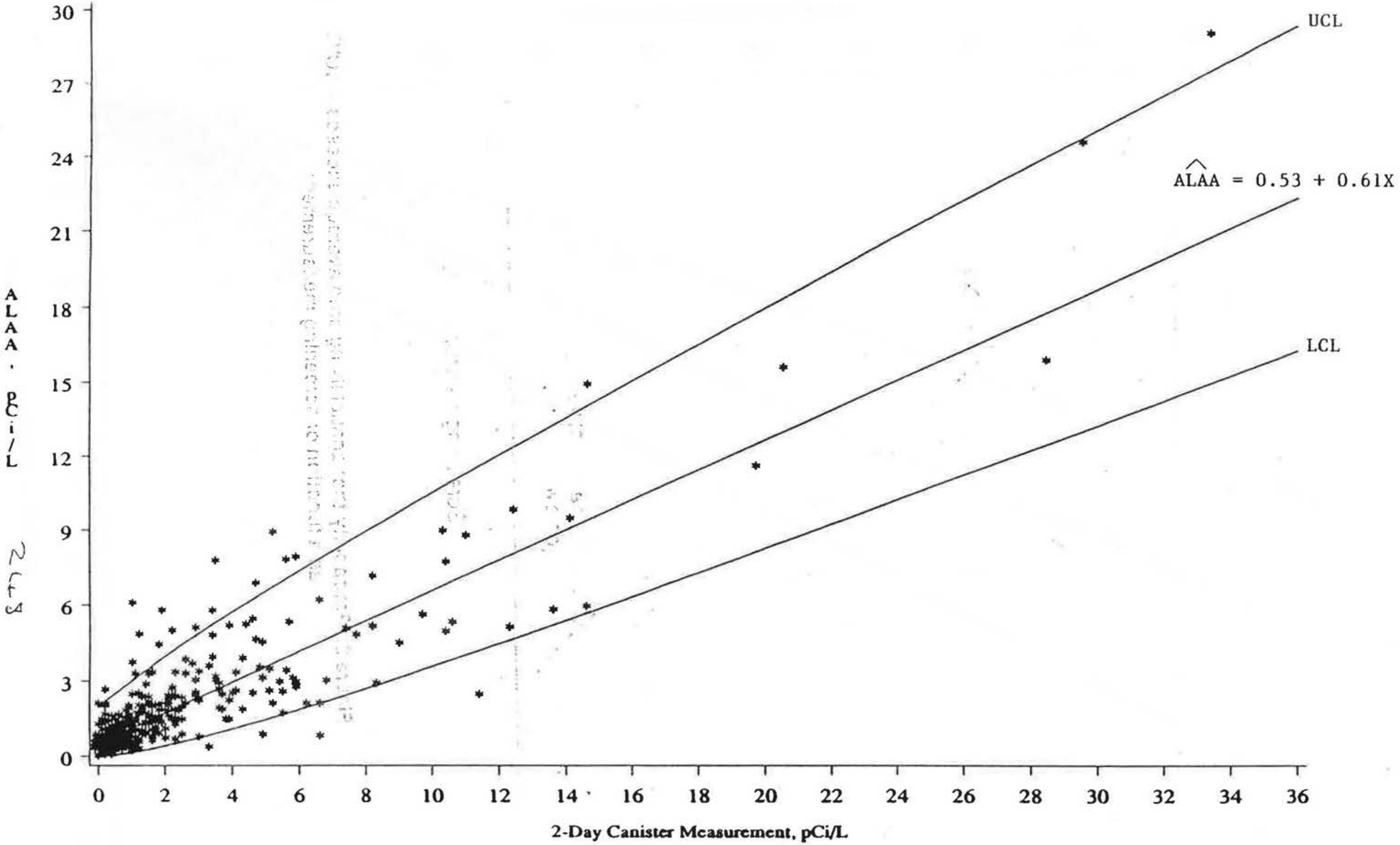

Figure 2. Relationship Between 2-Day Charcoal Canister Measurement And Annual Living Area Average - Nonbasement Houses

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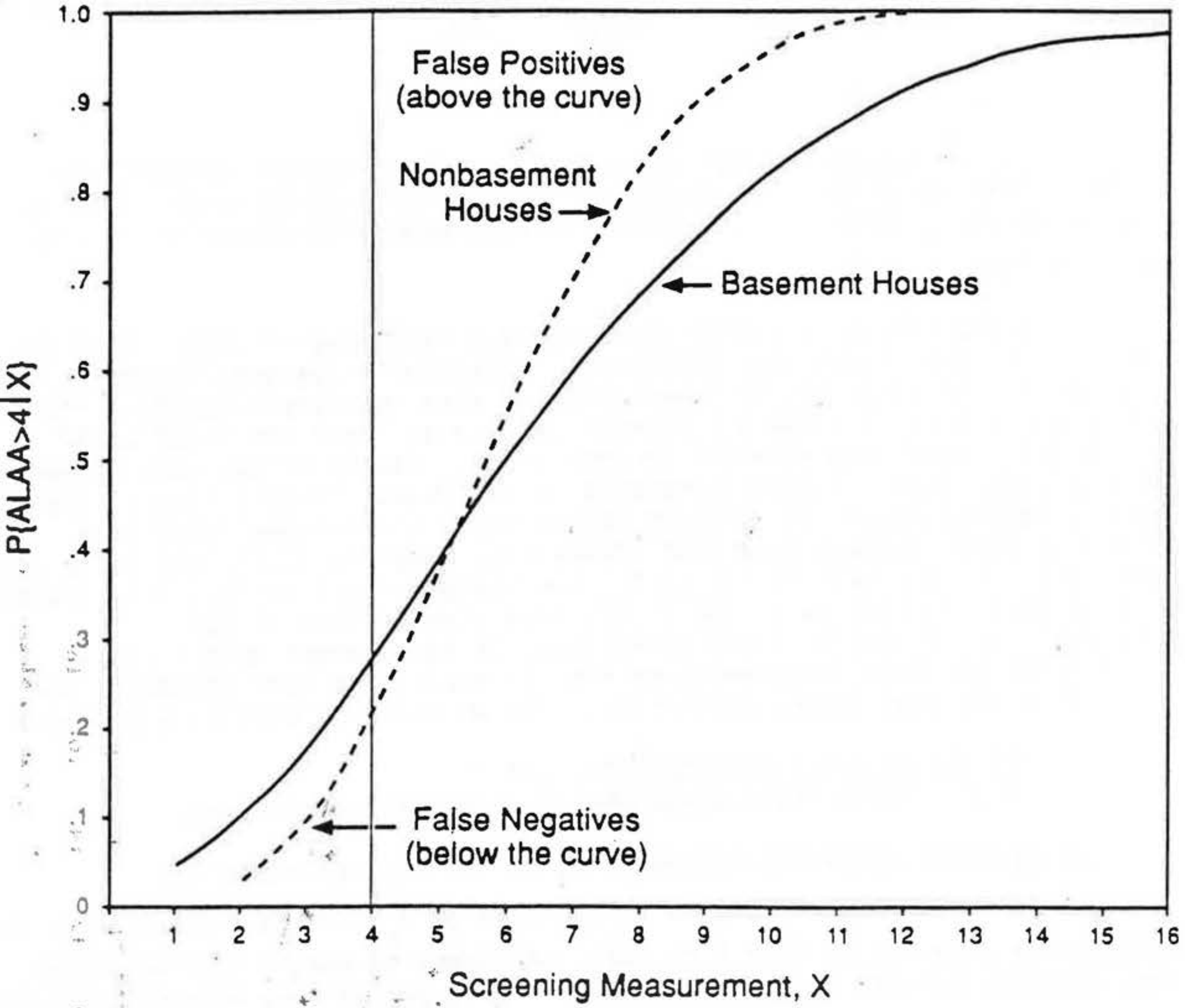

Figure 3. Probability that annual living area average exceeds 4 pCi/L as a function of screening measurement

For instance, the probability of a false negative error is approximately 0.17 for a screening measurement of 3 pCi/L in a basement house and approximately 0.09 for a screening measurement of 3 pCi/L in a nonbasement house. On the other hand, the probability of a false positive error is approximately 0.41 (= 1.00 - 0.59) for a screening measurements of 7 pCi/L in a basement house and approximately 0.29 (= 1.00 - 0.71) for a screening measurement of 7 pCi/L in a nonbasement house.

DISTRIBUTION OF $\widehat{ALAA}$

The relationships between short-term and long-term measurements of indoor ^{222}Rn as given by equations (3) and (4) provide an opportunity to use an existing data base of screening measurements to characterize the distribution of $\widehat{ALAA}$.

Under the EPA/State Indoor Radon surveys initiated in 1986, 30 of the 48 conterminous states have conducted statistically designed surveys. A probability-based sample of owner-occupied main residences having a listed telephone number, a permanent foundation, and at least one floor at or below grade level was selected in each state. Sample houses were tested with a 2-day charcoal canister placed in the lowest livable level. Tests were conducted during the heating season under close-house conditions. Although other surveys have used probability sampling (2,3), and other data sets include more test houses (4,5), the state surveys collectively provide the largest existing data base formed from studies that 1) use probabilities in making house selections, 2) have common objectives, 3) utilize the same measurement method, 4) employ the same protocol, and 5) sample the same target population. The 30 state surveys have produced

20,768 basement measurements, and
20,880 first floor measurements in nonbasement houses.

The basement screening measurement, X, for a given house was substituted into equation (3) to obtain a value of $\widehat{ALAA}$ for that house. In making the translation from X to $\widehat{ALAA}$, the sampling weight for the house was retained for use in future analyses. This process was repeated for all basement screening measurements and produced 20,768 $\widehat{ALAA}$ values and associated sampling weights from a random sample of basement houses covering a 30-state area. Similarly, each first floor screening measurement was substituted into equation (4). This generated 20,880 $\widehat{ALAA}$ values and associated sampling weights from a random sample of nonbasement houses covering a 30-state area.

Table 2 gives, in tabular form, the weighted cumulative distribution of $\widehat{ALAA}$ for basement houses, for nonbasement houses, and for all houses in the 30-state area. In addition, the distribution for basement and for nonbasement houses are presented graphically in Figure 4. Summary statistics (weighted) relating to these distributions of ALAA are given in

TABLE 2. CUMULATIVE DISTRIBUTIONS OF $\widehat{ALAA}$ FOR 30-STATE AREA

$\widehat{ALAA}$	Basement Houses	Nonbasement Houses	All Houses
.4	0.0	3.4	1.6
.6	0.1	12.9	5.9
.8	1.2	28.6	13.7
1.0	5.4	45.2	23.6
1.2	15.7	58.3	35.1
1.4	26.2	70.5	46.4
1.6	33.0	76.2	52.7
1.8	41.3	80.4	59.1
2.0	48.1	84.8	64.8
2.2	52.4	87.4	68.4
2.4	57.2	89.3	71.9
2.6	61.5	90.6	74.8
2.8	65.1	92.1	77.4
3.0	67.6	93.0	79.2
3.5	74.6	94.7	83.8
4.0	79.1	96.1	86.8
4.5	82.4	97.0	89.1
5.0	85.1	97.6	90.8
6.0	89.4	98.4	93.5
8.0	93.6	99.2	96.1
10.0	95.8	99.5	97.5
15.0	98.0	99.9	98.8
20.0	98.8	99.9	99.3
25.0	99.2	99.9+	99.5

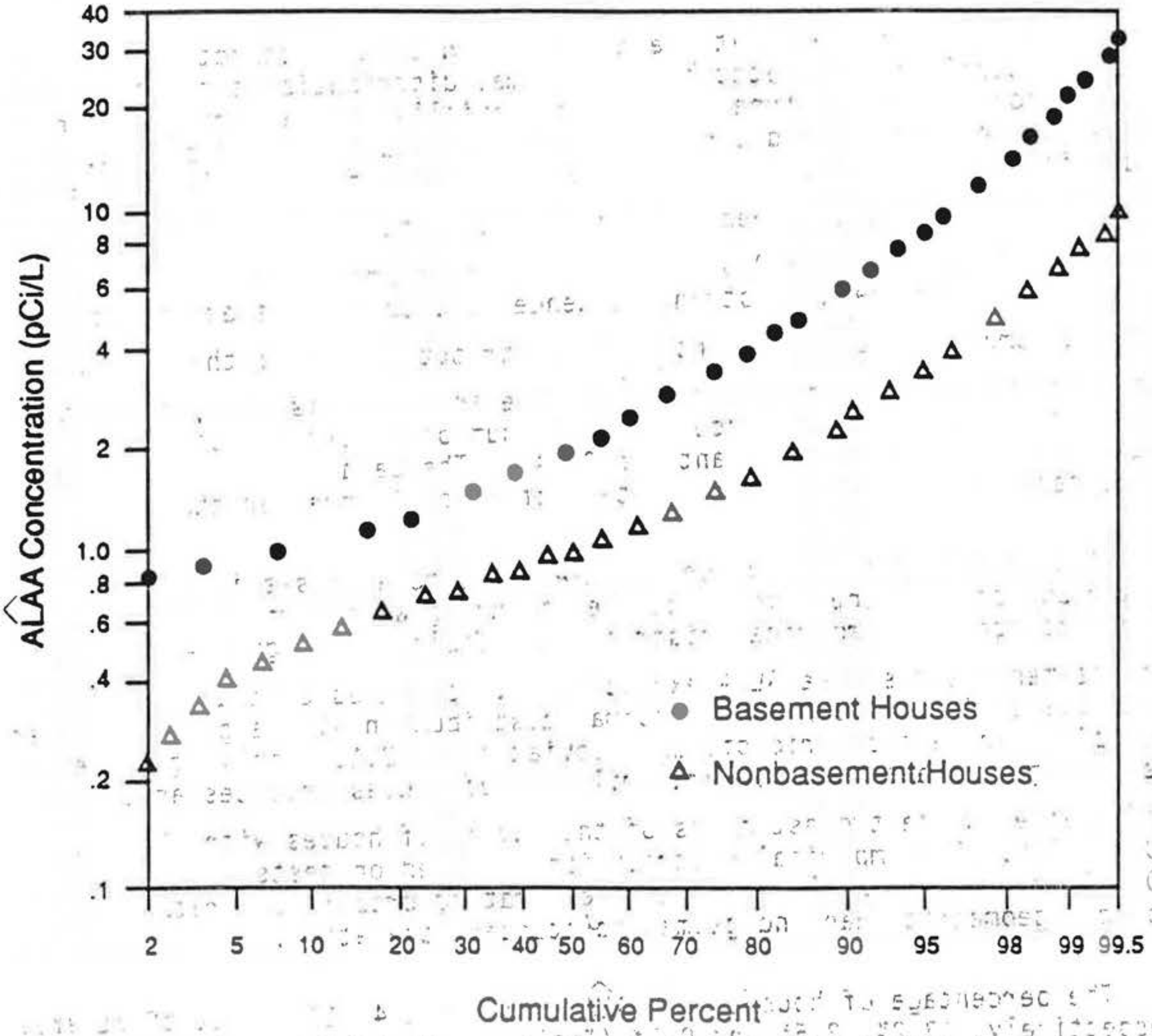

Figure 4. Normal probability plot of $\widehat{ALAA}$ for houses in 30-state area

Table 3. It is clearly evident that $\widehat{\text{ALAA}}$ is higher in basement houses. For example: the median (50th percentile) is 2.05 pCi/L for basement houses as compared to 1.02 pCi/L for nonbasement houses and the arithmetic mean for basement houses is more then double that for nonbasement houses (3.4 pCi/L as contrasted to 1.4 pCi/L).

Figure 4 indicates that the distribution of $\widehat{\text{ALAA}}$ cannot be satisfactorily approximated by a lognormal distribution since the data points for each house type depart substantially from a straight line plot. This was anticipated and can be explained by examining the prediction equations (3) and (4). Prediction equation (3), for example, converts the variable X, basement screening measurement, into the variable $\widehat{\text{ALAA}}$ through the relationship $\widehat{\text{ALAA}} = 0.69 + 0.54X$. X is assumed to be lognormally distributed and there is strong evidence to support this assumption. Under this assumption, $\widehat{\text{ALAA}}$ is lognormally distributed only if the intercept term in the relationship is zero. If the intercept is zero, then ln ($\widehat{\text{ALAA}}$) is normally distributed since it is the sum of a normally distributed variable (ln X) and a constant (ln 0.54). The data show, however, the intercept (estimated at 0.69) to be statistically greater than zero.

The empirical distribution of $\widehat{\text{ALAA}}$ shows more houses in the tail of the distribution than the number obtained by using a lognormal distribution. For instance, the empirical distribution (Table 2 or Figure 4) shows 1.2% of basement houses have $\widehat{\text{ALAA}}$ exceeding 20.0 pCi/L as contrasted to an estimate of 0.2% based on a lognormal distribution with a geometric mean of 2.4 pCi/L and a geometric standard deviation of 2.1. Applying these percentages to a base of several millions of houses produces an enormous difference in the two estimates of the number of houses with $\widehat{\text{ALAA}}$ exceeding 20.0 pCi/L. The empirical distribution is based on tests from more than 40,000 houses and should be used in estimating proportions rather than using a geometric mean and geometric standard deviation.

The percentage of houses with $\widehat{\text{ALAA}}$ exceeding 4, 10 and 20 pCi/L are, respectively, 13.2%, 2.5% and 0.7% (Table 3, 3rd column). In contrast, the distribution of annual average radon concentration in U.S. houses reported by Nero (6) shows: 7.4% of the houses above 4 pCi/L; 1.0% above 10 pCi/L; and, 0.13% above 20 pCi/L (these percentages were calculated using a geometric mean of 0.9 pCi/L and a geometric standard deviation of 2.8). The differences may be attributable, in part, to differences in the dependent variables, to the way basement houses are defined, and to the sampled populations. For this study, a basement house is defined as any house where the lowest livable level has at least one wall built against earth.

A scientific study is now under way by EPA to characterize the nationwide distribution of annual concentration of indoor ^{222}Rn in residential houses (7). This study should resolve many issues/questions

TABLE 3. ALAA SUMMARY STATISTICS FOR 30-STATE AREA

Parameter	Basement Houses	Nonbasement Houses	All Houses
Arithmetic Mean*	3.4	1.4	2.5
Geometric Mean*	2.4	1.1	1.7
Geometric Standard Deviation	2.1	2.0	2.2
Median*	2.05	1.02	1.50
% > 4 pCi/L	20.9	3.9	13.2
% > 10 pCi/L	4.2	0.5	2.5
% > 20 pCi/L	1.2	0.1	0.7

* Units of measurement - pCi/L.

relating to levels of ^{222}Rn to which occupants are exposed. Until such times that results from this national assessment study become available, the information provided by the distribution of $\widehat{ALAA}$ serves to add to the existing body of data on nationwide annual concentration of ^{222}Rn in the living area.

CONCLUSIONS

Two-day charcoal canisters and 1-year alpha track detectors were used to measure ^{222}Rn in 609 basement houses and 386 nonbasement houses. Results from this two-year study show there is a strong positive relationship between 2-day screening measurements and annual living area averages (ALAA). The equations for predicting ALAA from a screening measurement for basement and nonbasement houses are, respectively, $\widehat{ALAA} = 0.69 + 0.54X$ and $\widehat{ALAA} = 0.53 + 0.61X$. The results also show that ALAA varies widely among houses having the same screening measurement. The derived relationships were used to obtain predicted values of ALAA for a probability-based sample of 41,648 houses covering a 30-state area. A characterization of the distribution of predicted values for basement and for nonbasement houses is given. For example, an estimated 7.0% of the nonbasement houses have predicted values exceeding 3.0 pCi/L as compared to 32.4% for basement houses. To the extent that the 30 states represent the 48 conterminous states, the distributions of ALAA shown herein apply to the nation as a whole.

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