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HOUSE CHARACTERISTICS ASSOCIATED WITH GAMMA RADIATION AND RADON DAUGHTER WORKING LEVELS IN EASTERN PENNSYLVANIA

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Short Title: HOUSE CHARACTERISTICS AND INDOOR RADIATION

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Abstract--Working levels (WL) of radon daughters and γ measurements in basements are described for ~1200 houses near the Reading Prong. House variables studied included condition and construction materials of basement floors and walls, basement heights and areas, heating systems, air conditioning, water supply, and presence of drains and sump pumps. WL's were poorly predicted by house characteristics or γ measurements, while γ levels were well predicted by house characteristics and WL. Except for windowless basements, associated with both high γ and high WL measurements, factors predicting high γ levels tended to be associated with low WL's and *vice versa*. Dirt basement floors and fieldstone basement walls were strongly associated with high γ levels, as were poor wall conditions in multivariate analyses. Gamma levels were low in electrically heated homes. High WL's were strongly associated with electric heat, low WL's with basement walls of fieldstone and/or in poor condition. Large house volumes and well water supply were also associated with higher WL's.

INTRODUCTION

Predictors of radiation levels in homes, if readily observable, would be important to epidemiologists planning studies of cancer and indoor radiation. For retrospective case-control studies, such as of lung cancer and radon, an even higher importance could be placed upon readily observable predictors. Such predictors, in the case of radon in homes, could be background radiation, underlying geology and mineralization, topographical and/or pedological situation, or physical characteristics of house construction. We stress the "readily observable"; characteristics costly to measure, or for which permission is unlikely to be obtained if permission to measure radon is not obtained, are of less interest. We recognize that prediction may prove to be inadequate, but the topic is of sufficient importance that its pursuit is currently warranted.

In epidemiological studies, radon measurements will be unobtainable for a significant fraction of the present and prior residences of both cases and controls. Houses may no longer exist; houses may not be identified with certainty due to lack of information; or current residents or owners may be uncooperative. In these situations, rather than discarding observations or assuming mean values, it would be preferable to attempt to estimate missing values using predictors available from direct observation or the personal recollection of respondents.

In epidemiological studies, it is also likely that some strong correlate of lung cancer risk, such as tobacco smoking, will prove to be correlated with residential radon levels. Any such association would be unlikely to result from direct perceptions of radon, but rather would be mediated through socioeconomic factors. Socioeconomic factors will be associated with house characteristics and thereby with both construction characteristics of the home and with its topographic location. Knowledge of the empirical correlates of indoor radon levels would be essential to the statistical untangling of such observed relationships in the data-analysis phase of a study. Such weak associations, if not adjusted out, would be sufficient to bias results (in either direction) in epidemiological studies of the health end points which are the rationale behind the interest of research scientists, the radiation protection community, and society as a whole in the indoor radon issue.

For now, we must insist that associations which are of little utility in predicting radon levels in a specific house (a worthy goal, and a major interest of the radiation protection community), may still have utility when one is averaging across scores or hundreds of houses. In this paper, we present a preliminary analysis of spot measurements of gamma radiation and radon daughter working levels in homes in the vicinity of the Reading Prong in eastern Pennsylvania. In the near future, data from track-etch measurements of house radon, and from measurements of radon in water where available, will be analyzed in combination with the data presented here. However, both now and in the future, our emphasis is on readily observable correlates of the household radiation levels.

METHODS

The data reported upon were collected under the auspices of the Radon Monitoring Program of the Pennsylvania Department of Environmental Resources, working out of Gilbertsville, Pennsylvania. Measurements were collected over the period January 1985 through May 1986. Both the radiation measurements and the house descriptions were collected directly in the field by teams of trained staff.

Ludlum MicroR Meters Model 19 were used for γ measurements; the EDA Model 200 instrument for Kuznetz radon daughter (RnD) working level (WL) measurements. Measurements were made in the approximate center of the basement, and in the living or family room on the first floor. While both γ and WL measurements are usually available for the basement, only γ levels are generally available for the first floor. WL measurements were made over a five-minute period. Visits were scheduled by telephone in advance, and it was requested that the house be closed up for 12 hours prior to the scheduled measurement. In general, measurements were not made if the house had not been closed up. Track-etch detectors were left at the house at the time of the visit; a water sample was taken if a home had its own well, or shared a well with a few other homes.

During the visit, a detailed house description form was filled out by the field team.

Argonne National Laboratory (ANL) was permitted access to these data, and in 1986 an ANL team coded the hard-copy data on private residences for the computer. The data were entered and edited, and statistical analyses carried out, at ANL.

Results presented are for single-family residences. Measurements taken on repeat surveys, after any remediation, or where a note had been made indicating the house had not been closed up, are excluded. From these particular analyses, we have also excluded the relatively few houses with no basement whatsoever.

For the period January 1985 through May 1986, a total of 2096 residences were available. However, after September 1985 some homes had been visited because of high track-etch detector results obtained in a mail measurement program. A less-selected group (n=1873) of homes measured in the period January-September 1985, and a "core-area" group of homes (Boyerstown, New Berlinville, Barto, and Bechtelsville mailing addresses; n=1368) were also defined. The "core-area" homes include those on the Reading Prong in the area originally identified as at high risk of excessive radon levels. For purposes of analysis, the "core-area" is of interest because of the concerted effort made to measure all possible homes in these areas, thus yielding a more representative group of houses.

Results are presented here for the "core-area"; parallel statistical analyses of the three populations of homes as defined above were performed. Good general agreement was obtained among the three groups; a very high level of agreement was obtained for results from the "core-area" and "less-selected" groups.

Statistical analyses were carried out using SAS[1] one-way analysis of variance and multiple regression procedures. As used, comparing houses with a characteristic to homes without that characteristic (but not including those with missing information regarding that characteristic), the one-way analysis of variance is equivalent to a t-test. All statistics were performed on $\ln \gamma$ (μr/hr) and ln (WL + 1). House construction measurements were maintained in English/American units because category boundaries are sensitive to the units of measurement used in construction; it is also not necessarily the case that size-related effects are direct; they may reflect age or style-related construction details, or the topography on which the house is built.

RESULTS

Frequency distributions

Table 1 shows frequency distributions for both γ and WL measurements. The percent of measurements above currently recommended levels in habitable quarters is noted: a very high fraction of basements (46% for the WL, 25% for γ) fall above this level.

Regressing our 46 first-floor WL measurements on basement levels, and dividing expected values for the first floor by corresponding basement values, suggests that the ratio of first-floor to basement WL's was 65% at .02 WL and declined to 48% at .20 WL.

Construction correlates of γ exposure

Table 2 shows geometric mean γ levels according to a wide range of construction characteristics. The number of houses known to have the characteristic, the statistical significance, and a judgment score of the actual strength of the effect based primarily on the geometric mean are shown. Reliance upon statistical significance alone is hazardous: minor effects, if n is very large, may be highly significant; large effects, if n is relatively small, may be only marginally significant.

Most variables considered relate to basement construction, condition, and size. In general, γ levels are elevated in small, low basements in poor condition, and/or where walls are of fieldstone, there are no windows, and floors are partially of dirt and/or there is a partial crawl space. Very large basements, basements with concrete block walls, and basements with concrete floors had low γ levels.

Well water usage was not related to γ levels; electric heat was strongly associated with low γ; air conditioning was also associated with low γ, but the meaning of this is unclear since most measurements were not in the cooling season, and window units were not distinguished from central air conditioning.

There exists, obviously, a high degree of association among many of the construction variables, so stepwise multivariate regression analyses were undertaken. These also permitted concurrent analyses of the effect of radon daughters and of season on γ levels. Table 3 shows the results of the multiple regression analysis: stone basement walls dominate with well over half the total explanatory power of the model, followed by RnD WL's, which are only about one-third as influential. The seasonal effect is statistically significant but not very important for these basement measurements. Basement walls in fair/poor condition and some dirt floors (given fieldstone walls) added significantly in predicting higher γ levels. Electric heat and large basement volume were statistically significantly associated with lower γ levels even after adjustment for the other factors. The overall predictability of basement γ levels is impressive: an R^2 of .355 is quite good for an environmental study.

Even stronger is the predictability of first floor γ measurements from basement measurements, also shown in Table 3, where the R^2 was .72. Stone basement walls had a residual direct effect, air conditioning a slight negative effect.

The ratio of first floor to basement levels is strongly dependent upon both season and upon the actual basement γ levels. Winter, spring, and summer (few autumn measurements were available) were each assigned a dummy variable (0 or 1), and the regression $\ln \gamma$ (first floor) = $b_0 + b_1 \times \ln \gamma$ (basement) + $b_{2-4} \times$ seasons + $b_{5-7} \times$ (seasons x ln basement γ) computed. From the regression, a ratio of expected first floor γ to the corresponding basement γ can be calculated. In winter season, the ratio was .77 at 15 μr/hr, declining to .46 at 45 μr/hr. No strong effect of absolute γ levels was seen in the other seasons, when the first floor and basement levels were nearly identical, the ratios ranging from .91 to 1.04.

Construction correlates of RnD exposure

Univariate analyses of house construction variables affecting radon daughter working levels are also shown in Table 2. Of basement construction variables, only the few windowless basements and the largest basements showed notably elevated radon levels. Low basements, basements in poor condition, with fieldstone walls, or some dirt floors showed distinctly low radon levels. Presence of a sump pump was also associated with low radon levels.

Among the heating/cooling and water supply variables, only electric heat stood out, being strongly associated with high WL's. A well water supply was marginally associated with high radon levels. Non-electric heating variables are of course significant, due to the effect of the electric heat, but little difference is noted between homes with forced air and hot water heat.

Table 4 shows the results of stepwise multiple regression analyses of RnD WL's. The overall R^2 is .038, which is very low. The magnitude of some of the individual effects, however, is substantial: by mathematical chance, the regression coefficients can be read directly as WL's in the vicinity of the mean WL of this data set. A seasonal effect, as expected, did contribute to prediction. The three substantive variables which were retained all reflected different factors: basement size, electric heat, and well water supply.

DISCUSSION AND CONCLUSION

Figure 1 summarizes the data. There is a strong tendency for house construction variables associated with high radon-daughter working levels in the basement to be associated with low γ levels, and vice versa. This is apparent even without adjustment of data for the direct positive contribution of high radon levels to increased γ levels. The single exception to the relationship is the "windowless basement."

Age of house is not, unfortunately, available in our data set. Many individuals cannot give an accurate response immediately to a question concerning age of house, nor is it readily ascertained directly. A succession of house styles and construction characteristics has occurred over time, however, and home construction characteristics are highly correlated with the age of the house. Age of house is not a single variable: both construction characteristics and age per se are involved. Changes in houses over time, as undersoil settles and joints loosen may be important and should be investigated.

In Figure 1 there is an evident association of house age with radiation. Older houses whose basements have some or most of the characteristics of dirt floor, fieldstone walls, poor wall condition, low basement walls, and small house volume are associated with high γ and low radon levels (unless the basement is windowless, which does tend to occur in older homes).

Modern homes with electrical heat and large floor areas tend to have high radon levels and low γ levels. The minimal difference between houses with hot water and forced air heat was unexpected: a greater difference may be seen in first floor RnD levels.

Use of private well water is also associated with higher radon-daughter levels; we await analyses including the water radon levels before concluding whether the relationship is due directly to radon in water, reflects outer suburban or rural location, or is related to topography. Quantitatively, the effect (~.03 WL where average basement levels are ~.05 WL) is an order of magnitude larger (assuming a 50% equilibrium ratio) than that estimated by Nazaroff et al.[2] for the average contribution of private wells to house radon levels in the U.S.

The correlations described above may or may not prove to be usefully applied to other geographic areas. It is our impression that the unique topography and geology of each area, in combination with its historical and recent settlement patterns and changing construction practices, may determine the relationships such as we have just analyzed. These relationships need to be confirmed anew in each region studied. For an epidemiologist, to whom these relationships are but a tool in the analysis of the data from a single study, the generalizability of such relationships over broad regions is of lesser concern.

Also, for epidemiologists, grab-sample measurements in basements have a clear utility. Many epidemiology studies will include a grab (or short-term) sample of radon on a first visit to a home to minimize the loss of information involved in collecting track-etch detectors after some months (~20% loss in 6 months in our experience). It is also likely that ethical constraints will require immediate notification of householders with high radon levels, which will limit the value of long-term (>1 month) measurements.

Single grab samples have proven to track well with track-etch detector results when the grab samples are taken from basements under controlled conditions, according to unpublished ANL results and those of others(3), at least under conditions where the range of radon values is broad enough to be of epidemiological interest. It is also true that basement radon levels are very nearly as highly correlated with personal contamination by radon daughters as are main floor and bedroom measurements(4). In summary, basement measurements, and grab or short-term samples, will play a significant role in the epidemiology of health effects of radon. We conclude that more emphasis on estimating living area radon-daughter levels from basement radon levels, and estimating multi-year radon levels from short-term measurements, is warranted.

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Table 1. Radiation levels in Pennsylvania homes

Quantile (%)	γ (μr/hr) First floor	γ (μr/hr) Basement	RnD (WL) Basement
25	7.5	9	.007
50	10	11.5	.018
75	12.5	15	.047
90	16	19	.136
95	18	23.5	.224
99	25	35	.943

Table 2.--House construction characteristics as related to basement radiation levels*

Construction variables	γ (μr/hr) n	Geom. mean	p	Effect	RnD (WL) n	Geom. mean	p	Effect
Basement floor variables								
Crawlspace, some	254	12.6	.003	+	165	.057	.73	none
Concrete floor, all	868	11.1	<.0001	--	1060	.056	.07	none
Dirt floor, some	89	15.4	<.0001	++	108	.040	.07	--
Sump pump	220	11.3	.45	none	265	.041	.048	--
Drain	646	11.6	.40	none	782	.057	.46	none
Floor cracked thru	442	12.0	.048	+	494	.055	.79	none
Basement wall variables								
Concrete block	651	10.3	<.0001	--	824	.062	<.0001	+
Fieldstone	218	16.2	<.0001	++	249	.036	.0004	--
Concrete	66	11.0	.32	none	78	.045	.43	none
Without windows	31	14.6	.018	+	44	.082	.39	++
Cracks noted	282	13.2	<.0001	+	327	.047	.24	none
Wall condition:								
Good	690	10.5	<.0001	--	866	.058	.06	none
Fair	233	14.2	<.0001	+	265	.045	.15	none
Poor	29	16.5	<.0001	++	27	.025	.001	--
Basement size variables								
Wall height:								
>8 ft (>2.4 m)	62	10.0	.011	--	73	.051	.68	none
5.6-8 ft	864	11.5	.35	none	1064	.055	.06	none
<5.5 ft (<1.7 m)	48	12.7	.044	+	52	.029	.012	--
Area:								
>1300 ft² (>120.8 m²)	212	10.6	.002	--	239	.075	.003	++
751-1300 ft²	427	11.0	.004	--	526	.048	.26	none
<750 ft² (<69.7 m²)	291	12.9	<.0001	+	374	.043	.07	none

Table 2.--(Cont'd.)

Construction variables	γ (μr/hr) n	Geom. mean	p	Effect	RnD (WL) n	Geom. mean	p	Effect
Heating/cooling and water variables								
Well water supply	341	11.3	.42	**none**	341	.065	.08	+
Air conditioning	304	10.7	<.0001	--	380	.042	.004	--
Forced air heat	231	11.9	.15	**none**	281	.041	.008	--
Electric heat	148	9.5	<.0001	--	185	.085	.009	++
Hot water heat	411	12.3	<.0001	+	492	.045	.022	--
Other (wood/kero)	33	12.7	.19	+	54	.067	.50	**none**

*One-way analyses of variance of ln γ (μr/hr). N's are numbers of houses with characteristic, p's the probability that they are homogeneous with other houses with non-missing information for the same variable. "Effect" is a judgment of the strength of the effect, based primarily on the geometric mean.

Table 3. Stepwise regression estimates of γ levels[*]

Variables	F	Regr. coeff.
Basement γ (ln μr/hr)[†]		
Stone basement walls	204.5	+.34
Radon daughter levels (ln (WL+1))	63.5	+1.08
Basement wall condition fair/poor	27.8	+.15
Cosine (6.28318 x day of year/365)	15.2	+.094
Electric heat	14.0	-.13
Basement floor some/all dirt plus walls of stone	7.36	+.17
Basement volume (ft^3)	7.31	-.0000086
Intercept	--	2.36
First floor γ (ln μr/hr)[‡]		
Basement γ (ln μr/hr)	1267.	+.68
Stone basement walls	21.6	+.10
Air conditioning	7.5	-.05
Intercept	--	+.61

[*]Unless noted otherwise dummy variables were used, 1 indicating "present," 0 "absent."

[†]All p's <.001; R^2 = .355.

[‡]All p's <.01; R^2 = .716.

Table 4. Stepwise regression estimates of radon daughter working levels*

Variables	F	Regr. coeff.
Basement RnD (ln(WL+1))†		
Basement volume (ft^3)	9.00	+.0000026
Cosine (6.28318 x day of year/365)	11.6	+.023
Electric heat	5.24	+.023
Water from well	12.0	+.030
Intercept	--	+.0248

*Unless noted otherwise dummy variables were used, 1 indicating "present," 0 "absent."

†All p's <.025; R^2 = .038.

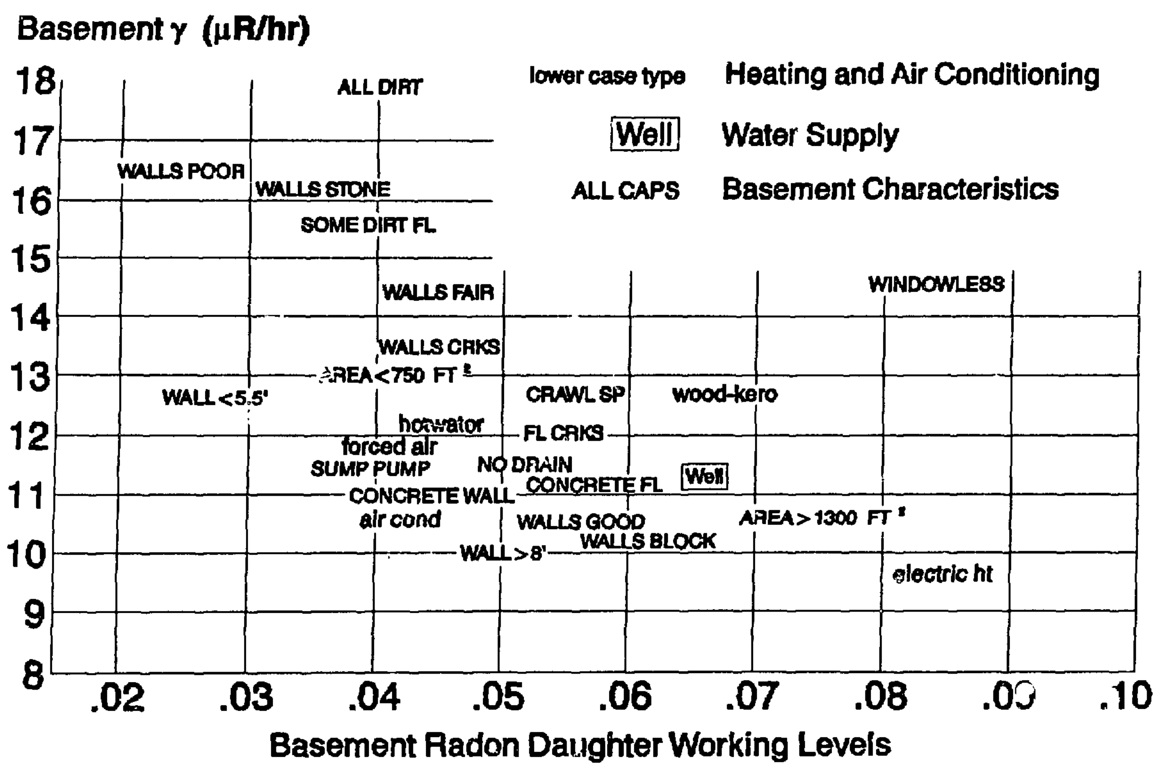

Figure 1. House construction characteristics by basement γ and radon daughter WL's