ARTICLES

Indoor Radon and Lung Cancer in China

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Radon has long been known to contribute to risk of lung cancer, especially in underground miners who are exposed to large amounts of the carcinogen. Recently, however, lower amounts of radon present in living areas have been suggested as an important cause of lung cancer. In an effort to clarify the relationship of low amounts of radon with lung cancer risk, we placed alpha-track radon detectors in the homes of 308 women with newly diagnosed lung cancer and 356 randomly selected female control subjects of similar age. Measurements were taken after 1 year. All study participants were part of the general population of Shenyang, People's Republic of China, an industrial city in the northeast part of the country that has one of the world's highest rates of lung cancer in women. The median time of residence in the homes was 24 years. The median household radon level was 2.3 pCi/L of air; 20% of the levels were greater than 4 pCi/L. Radon levels tended to be higher in single-story houses or on the first floor of multiple-story dwellings, and they were also higher in houses with increased levels of indoor air pollution from coal-burning stoves. However, the levels were not higher in homes of women who developed lung cancer than in homes of controls, nor did lung cancer risk increase with increasing radon level. No association between radon and lung cancer was observed regardless of cigarette-smoking status, except for a nonsignificant trend among heavy smokers. No positive associations of lung cancer cell type with radon were observed, except for a nonsignificant excess risk of small cell cancers among the more heavily exposed residents. Our data suggest that projections from surveys of miners exposed to high radon levels may have overestimated the overall risks of lung cancer associated with levels typically seen in homes in this Chinese city. However, further studies in other population groups are needed to clarify the carcinogenic potential of indoor radon. [J Natl Cancer Inst 82:1025–1030, 1990]

Investigations of cancer risk among underground miners in several areas of the world, including the People's Republic of China, provide conclusive evidence that radon is a lung carcinogen *(1–4)*. Radon is a noble gas that decays into radioactive daughter products at a relatively fast rate (half-life = 3.8 days). Radon and her daughter products emit alpha particles that are implicated in the cellular changes leading to lung cancer. In the studies with miners, exposure to high radon levels was typical. These exposures often led to large (>20-fold) increases in lung cancer among the most heavily exposed. In a few miner cohorts, however, significant increases in risk were observed at levels nearly as low as those that may result from long-term residential exposures *(5,6)*.

Based on studies of underground miners, and assuming a linear relationship between excess risk and exposure, increases of twofold or more in lung cancer risk have been projected at the lower doses associated with some long-term residential exposures to radon. Indeed, in the United States, it has been estimated that 6,600–24,000 lung cancer deaths per year may be related to indoor radon *(7)*. Indoor radon accounts for nearly half of all radiation exposures in the general population *(8)*, and thus it is not surprising that radon has become a major public health concern.

Several studies, mostly in Sweden, have directly assessed lung cancer risks according to housing characteristics. These studies have often, but not always, found evidence of increased risk among those subjects residing in homes where radon levels were thought to be high *(1)*. Most of these investigations were based on small numbers of subjects, however, and few incorporated actual measurements of radon in the homes.

In this presentation, we report findings from a relatively large, population-based, case–control study of lung cancer among women in northern China. The study was initiated to evaluate causes of the exceptionally high rates of lung cancer among women in Shenyang, the capital of Liaoning Province. In Shenyang, the average, annual, age-adjusted (world standard) mortality rate for women with lung cancer in the mid-1980s was 33 per

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100,000 (Liaoning Public Health and Epidemic Station: unpublished data). The similarly adjusted rate for US women was 22 per 100,000 *(9)*. The major risk factors were cigarette-smoking and air pollution, especially indoors, as reported elsewhere *(10)*. Anecdotal evidence of high radon levels in Shenyang, as well as growing international interest in the effects of radon, prompted us to include measurements of household radon exposure taken over 1 year for examination in relation to lung cancer risk.

Methods

Population Studied

Eligible patients with lung cancer were female residents of Shenyang who were 30–69 years old and had primary lung cancer (International Classification of Diseases-9 classification system, code 162) diagnosed between September 1985 and September 1987. The cases were identified through the Shenyang Cancer Registry, which covered all area hospitals. A special rapid reporting system was established in which all suspected lung cancer diagnoses and supporting diagnostic materials (pathology and cytology slides and x rays) were reviewed and classified by an expert panel of pulmonary disease physicians and pathologists. This panel met weekly during the study period.

Control subjects were women randomly selected from 5-year age strata of the Shenyang general population. The numbers in each age group were selected in advance so that the age distribution of the control subjects would be similar to the age distribution of women with lung cancer previously reported to the cancer registry. A three-stage sampling procedure was used. To choose each control subject, we first selected a neighborhood committee—one of approximately 1,400 administrative units covering a geographic/administrative area of the city. We sampled randomly with replacement, weighting each committee according to its population. Then, one household from each committee was randomly chosen, and a listing of its members was obtained. Finally, one woman from among those in the particular age group was randomly chosen.

Interviews

Trained nurse interviewers sought personal interviews with each patient and each control subject, except for those who were too ill or deceased. For most patients, the time between diagnosis and interview was less than 1 month. A structured questionnaire was used to inquire about residential histories and housing characteristics, such as sources of indoor air pollution from home heating and cooking devices, for all residences lived in for 3 or more years. Information on smoking status, occupation, prior medical conditions, and other factors was also obtained. For the questionnaire, smoking was defined as use of cigarettes for 6 months or longer.

Dosimetry

Six months after the start of the study, the interviewers asked permission to install alpha-track detectors (type SF, Terradex Corp., Glenwood, Ill) in the homes of patients and control subjects. For those who had lived in their current residence for less than 5 years, detectors were placed in the previous residence, provided that *(a)* the residence was in Shenyang, *(b)* the residence was accessible, and *(c)* the subject had lived there at least 5 years. Two detectors were placed in each house; usually, one was placed in the bedroom and one in the living room. Typically, they were placed on furniture or hung at eye level.

Homes in Shenyang are relatively small, usually consisting of a few rooms on one floor and often without partitions between living areas. Residents were instructed not to disturb the detectors. One year after the detectors were placed in the homes, they were collected by field supervisors and sealed in their original foil containers for shipment to the United States. Radon levels were measured in picocuries per liter, which is a measure of the rate of radioactive decay equivalent to about 2 disintegrations per minute in 1 L of air. At equilibrium, 100 pCi/L = 1 Working Level (WL), which is the unit of radon daughter concentration used in studies of miners. It is equal to any combination of radon progeny in 1 L of air that will ultimately release 1.3×10^5 MeV of potential alpha energy during decay. All measurements were standardized for the number of days the detector was in the home.

The detectors consist of plastic film (CR-39) enclosed in a small cylindrical chamber covered by a paper filter. The filter allows the passage of radon gas, but not daughter products. Alpha particle emissions from the decaying radon make tracks in the film, which are later chemically enhanced and then counted. An atmospheric concentration of radon of 1 pCi/L would produce about 180 tracks in 1 year. The precision of these detectors has been estimated to be within ± 10%; they are less precise at very low exposure levels *(11)*.

Statistical Analysis

Odds ratios were calculated as measures of association between radon exposure and lung cancer risk *(12)*. Logistic regression models were used to adjust the odds ratios for age, education, and smoking status. Categories for use of cigarettes were nonsmokers, light smokers (those who smoked for <30 yr or smoked 1–19 cigarettes per day for <40 yr), and heavy smokers (those who smoked >=20 cigarettes for >=30 yr or smoked for >=40 yr). In addition, the odds ratios were adjusted for an index of average indoor air pollution from home heating and cooking sources, which was categorized as low, moderate, and high *(10)*. We used both the average and the maximum of the two radon readings in the home as the dose measure. Because the patterns were similar for each, we present data only for the maximum values.

Results

Of the individuals interviewed, 391 control subjects and 397 patients had detectors installed in their homes. These numbers represent 99% of all control subjects interviewed and 95% of all patients with lung cancer; 5% of the patients were not interviewed because of death, sickness, undetermined location, or refusal to cooperate. Detectors were collected 1 year after installation for 330 of the cases and 362 controls. Some detectors were not recovered due to the resident's refusal to give up the detectors, the resident's movement from the home, or destruction or loss of the detectors. For an additional 22 cases and six controls, the detectors were unreadable. Thus, 308 cases and 356 controls were entered in the study; they represented 79% and 91% of those eligible, respectively. Radon measurements were available for 1,291 detectors; only one of the two detectors was returned for 6% of all subjects.

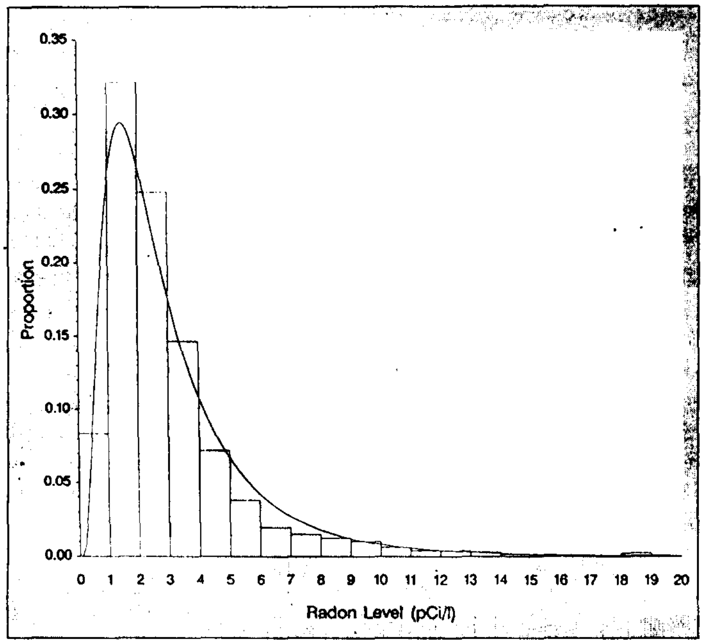

Figure 1. Distribution of radon levels in homes in Shenyang, People's Republic of China, 1986–1987. Smooth curve represents log normal fit to the observed distribution

The median number of residences reported by the study participants was three (maximum, eight). The median time of residence in the last home was 24 years; 76'% lived there for more than 10 years. On average, the individuals had lived 66% of their adult lives in the homes where radon was measured.

Of the 664 study participants, we found that 70% of the subjects lived in single-story houses or on the ground floor of dwellings with two or more stones. Most (70%) of these residences had cement floors; the remainder usually had brick or wood floors. Basements were extremely rare.

The median radon level was 2.3 pCi/L (range, 0.1–55.4). The measurements were well described by a log normal distribution (fig. 1), with a geometric mean of 2.4 pCi/L. The percentages of readings in the categories 0.1–1.9, 2.0–3.9, 4.0–7.9, and >=8.0 pCi/L were 40.5%, 39.4%, 14.4%, and 5.7%, respectively. When we used the greater of the two radon determinations to classify the home's radon level, the percentages in the four categories were 28.0%, 42.0%, 20.6%, and 9.3%, respectively. A significant correlation (r = .52, P < .001) between the readings from the pairs of detectors placed in each home was observed. Among the paired measurements, 77% were within 2 pCi/L; for 78%, the ratio of the two readings differed by a factor of less than two.

Home radon levels varied considerably (P < .01) according to floor; the levels were higher in single-story dwellings and on the first floor of dwellings with two or more stories (table 1). In addition, radon levels tended to be higher (P < .01) in homes with elevated levels of air pollution from heating and cooking sources. Differences according to year the house was built or cigarette-smoking status were not significant (P > .20) (table 1).

The medians of the maximum radon levels were 2.8 pCi/L for the homes of patients with lung cancer and 2.9 pCi/L for the homes of control subjects. Table 2 shows the odds ratios associated with radon levels for different types of lung cancer. The odds ratios are adjusted for age, education, smoking status, and an index of indoor air pollution. Further adjustment for floor of residence or year the home was built resulted in only minor changes. Except for a slightly upward trend for small cell carcinomas, no evidence of increasing risk with increasing radon level was found. In fact, risks overall tended to be somewhat lower among those exposed to the highest radon levels. The odds ratios and corresponding 95% confidence intervals for the four categories of radon levels were 1.0 (referent category), 0.9 (0.6–1.3), 0.9(0.5–1.4), and 0.7 (0.4–l.3). When analyses were restricted to those who had lived in their last residence at least 25 years, the odds ratios and 95% confidence intervals for the four radon categories were 1.0 (referent category), 0.7 (0.4–1.4), 1.2 (0.6–2.3), and 0.7 (0.3–1.6).

Table 3 shows odds ratios associated with home radon levels and smoking status. Risk of lung cancer tended to rise with increased smoking in each radon-exposure category. The trends

Table 1. Distribution of home radon levels for controls according to housing characteristics and smoking status

Characteristic	No. of controls†	% of controls with home radon level (pCi/L)*			
		0.1-1.9	2.0-3.9	4.0-7.9	≥8.0
Floor where subject lives					
1	241	21	42	24	13
2 or above	101	40	39	17	4
Year built					
Before 1950	117	21	42	25	12
1950 or after	214	29	40	22	9
Index of indoor air pollution					
Low	140	36	36	19	8
High	216	20	45	23	12
Smoking status‡					
None	103	21	40	27	12
Husband only	122	32	39	21	8
Self	131	26	45	18	11

*The higher reading from the two alpha-track detectors is used.
†Individuals with missing information on the housing characteristic were excluded in the analysis of that characteristic.
‡Smoking is defined as the use of cigarettes for 6 months or longer.

Table 2. Odds ratios for lung cancer by histologic type according to home radon level*

Cell Type	Odds ratio for radon level (pCi/L)			
	0.1–1.9	2.0–3.9	4.0–7.9	>=8.0
Squamous cell carcinoma	1.0 (20, 95)	1.0 (35, 148)	0.7 (10, 77)	0.8 (7, 36)
Small cell carcinoma	1.0 (8, 95)	1.2 (16, 148)	1.7 (10, 77)	1.4 (5, 36)
Adenocarcinoma	1.0 (34, 95)	0.6 (35, 148)	0.8 (21, 77)	0.4 (5, 36)
Other or unknown	1.0 (29, 95)	1.0 (45, 148)	0.9 (19, 77)	0.8 (9, 36)
All histologic types	1.0 (91, 95)	0.9 (131, 148)	0.9 (60, 77)	0.7 (26, 36)

*Odds ratios are adjusted for age, education, smoking status, and an index of indoor air pollution. Values in parentheses = No. of cases and controls. The higher reading from the two alpha-track detectors is used.

Table 3. Odd ratios for lung cancer according to smoking status and home radon level*

Smoking status	Odds ratio for radon level (pCi/L)				Total
	0.1–1.9	2.0–3.9	4.0–7.9	>=8.0	
Nonsmoker	1.0† (41, 61)	0.8 (46, 89)	0.8 (27, 53)	0.6 (9, 22)	1.0
Light smoker‡	3.0 (30, 16)	1.5 (41, 40)	1.4 (18, 20)	1.7 (8, 7)	2.2
Heavy smoker§	1.9 (20, 18)	4.3 (44, 19)	6.8 (15, 4)	2.3 (9, 7)	4.2
Total	1.0	0.9	0.9	0.7	

*Odd ratios are adjusted for age, education, and an index of air pollution. Values in parentheses = No. of cases and controls. The higher reading from the two alpha-track detectors is used.

†Reference category.

‡Light smokers are defined as those who smoked for <30 yr or smoked 1-19 cigarettes per day for <40 yr.

§Heavy smokers are defined as those who smoked >=20 cigarettes for >=30 yr or smoked for >=40 yr.

were not as strong as those in western countries in large part because amounts smoked in Shenyang were low; for cases, the median number of cigarettes smoked per day was seven.

In contrast to the clear trend of increased risk of lung cancer with increased smoking, we observed no trend of increased risk with increasing radon level in nonsmokers or in light smokers. Risks were higher for heavy smokers exposed to radon levels greater than 2 pCi/L, compared with those exposed to lower levels. This interaction between smoking status and radon, however, was not statistically significant (P = . 15). When averages of the two radon readings were used rather than the maximum values, little change was observed in the odds ratios presented in tables 2 and 3.

Discussion

The results of this case–control study, which was conducted in an area with exceptionally high rates of lung cancer among women, indicate that the indoor radon level is not likely to contribute to the elevated incidence in Shenyang. Little evidence of an increased risk of lung cancer with increasing radon exposure was found, except for a slight association with small cell carcinomas. The link to this histologic type of cancer is interesting, however, since the relative increases in risk reported among underground miners tend to be greater for small cell cancers than for other forms of lung cancer *(1–4)*.

Prior Studies of Household Radon

Our findings add to a relatively small number of epidemiologic investigations of lung cancer in relation to household radon exposure. Although it has long been known that exposure to high levels of radon accounts for the high rates of lung cancer among various groups of underground miners, including those in China *(13)*, the possibility of an elevated risk among persons exposed to much lower levels of radon in their homes was not suggested until recently. In 1979, Axelson *(14)* reported an increased lung cancer risk associated with living in stone houses compared with living in wood houses. Subsequent case–control studies in Sweden *(1, 15)* also showed positive associations between risk of lung cancer and living in structures where radon levels were estimated to be high. However, several of these studies were based on small numbers (<40) of cases. A larger investigation in northern Sweden *(16)* found no difference in lung cancer risk between those living in wood and nonwood residences. In Stockholm, increases in risk of about twofold, but no dose–response trends, were found for residents of houses classified as having high radon levels based on geologic considerations and/or short-term radon measurements *(17, 18)*. In southern Sweden, a positive association of risk of lung cancer was found in rural but not urban areas *(19)*.

The data are more limited outside Sweden. A follow-up study in Maryland *(20)* found no appreciable differences in lung cancer risks according to housing characteristics. A small study (27 cases) in Ontario (Canada), however, reported a nonsignificant twofold increase in lung cancer among residents of homes built with radioactive materials *(21)*. In a study of New Jersey women, lung cancer risk was increased more than twofold among those living in homes with radon levels of >=4 vs. <1 pCi/L, but the group exposed to >=4 pCi/L consisted of only six cases and two controls *(22)*.

Few of these studies involved measurement of radon. Except for the New Jersey study, the approach has been to use short-term

(2 wk–2 mo) measurements to assign average radon levels to specific housing types and then to classify individuals according to housing type rather than according to observed radon levels. In contrast, we had year-long radon determinations for all subjects and classified each woman according to the radon level measured in her home. This method resulted not only in more specific estimates of exposure, but also in wider variation that increased the power to detect associations, including dose–response trends. Thus, it is noteworthy that we could not replicate the Swedish or New Jersey findings even though our study was of sufficient size to detect, with high (>80%) statistical power, a 1.7-fold increased risk of lung cancer among those living in homes with radon levels greater than or equal to 4 pCi/L, compared with levels of less than 2 pCi/L.

Other Risk Factors

In our study, confounding by other risk factors may have hindered detection of increased risks among women exposed to high radon levels.

Indoor air pollution in Shenyang, which is very high by western standards, was shown to be associated with increased lung cancer risk *(10)*. During winter, indoor concentrations of benzo *[a]* pyrene in single-story houses in Shenyang averaged more than 70 ng/m^3, a value more than 70 times higher than the median level in US cities in the 1970s *(10,23)*. The high pollutant levels may provide aerosols to which radon-decay products can attach.

Because attached radon-decay products are not as readily deposited in bronchial and lung airways *(24)*, alpha radiation exposure of lung tissue may be reduced. We adjusted for an index of indoor air pollution in our analyses, however. We did not find positive associations between radon and lung cancer for residences with either low or high indoor air-pollution levels, although even homes with low levels would be considered dusty by western standards.

Smoking also increases room aerosols, but in this population, the high exposure to pollutants from coal-burning heating and cooking systems in the home seems to have a greater association with risk than environmental tobacco smoke. Cigarette smoking, a strong risk factor that accounts for about 40% of the lung tumors among women in Shenyang *(10)*, did not confound the association between radon and lung cancer. However, interaction between smoking status and radon was suggested by a negative trend in risk with increasing radon level among nonsmokers and light smokers and by a modest upward trend among heavy smokers. Studies of underground miners show that smoking and radon combine synergistically to enhance lung cancer risk *(2)*.

Exposure Estimates

Our study may also have been hindered by imprecision in exposure estimates. Although we used a radon detector considered to be the most appropriate available *(11)*, it is possible that some measurements were affected by high indoor dust levels common in Shenyang. However, among controls, radon levels did not decline with increasing indoor pollution, and our use of the maximum of the two readings should have reduced the possibility of artificially low levels due to clogged detectors. The alpha-track detectors were also in place for a full year, minimizing seasonal variation and increasing the reliability of the radon exposure estimates.

The highly significant correlation between readings from the pairs of detectors, which were often placed in the same or adjacent rooms, suggests that the radon determinations are reproducible and probably reliable. The homes in Shenyang are typically smaller than those in western societies and often have only a limited living and sleeping area. Thus, the measurements were taken where the individuals actually spent much of their lives.

In contrast, some of the home radon readings elsewhere have come from measurements taken in living areas such as basements, which are used sparingly by most families *(1)*. It is noteworthy that a recent survey in Colorado *(25)*, using 1-year alpha-track measurements in living areas, reported a distribution of radon levels very similar to that in Shenyang. The median level in Colorado was 2.5 pCi/L; 20% of the levels were >4,0 pCi/L.

The radon determinations should thus be relatively accurate reflections of recent exposure. Although the correlation between current and past radon exposures is uncertain, it is likely to be higher in Shenyang than in other areas of the world where the population is more mobile. Most persons in this study had been long-term residents (median, 24 yr) of the homes where the measurements were taken, and modifications to the homes during this period were rare (3%). Because radon exposures during the 5–15 years prior to lung cancer onset are thought to impart the highest risk *(2)*, our measurements should typify exposures that are especially relevant.

Comparison of the radon levels observed in Shenyang with those observed in studies of underground miners is informative, even though there are notable differences in host and exposure characteristics between our population survey and the cohort studies of miners. These differences may contribute to the lack of comparability of study findings. For example, the miner studies in large part involved men, smokers, a very dusty and polluted atmosphere, exposure to varying levels of radon, usually over a limited number of years, and cumulative exposure estimated from intermittent sampling. Our study, on the other hand, involved only women, mainly nonsmokers, a somewhat dusty environment (though not equivalent to an underground mine) containing coal-combustion products, apparent exposure to relatively constant low levels of radon over many years, and exposure estimates based on recent conditions in the home.

Under certain assumptions of occupancy and radon equilibrium, an exposure to 1 pCi/L for 1 year is thought to be roughly equivalent to 0.2 Working Level Months (WLM). The WLM is the unit of exposure used in the miner studies that results from inhaling air with a concentration of 1 WL of radon daughters for 170 hours *(7)*. The median concentration in our highest category of radon levels (>=8 pCi/L) was 10.7 pCi/L. Exposure for 24 years would thus result in an estimated 51 WLM; it would be 7 WLM for our low radon-exposure category (<2 pCi/L), which had a median reading of 1.4 pCi/L.

Based on recent projections from risk assessment models derived from miner studies *(2)*, we would have expected an 80% excess (odds ratio, 1.8) of lung cancer in our high radon-exposure category compared with our low radon-exposure category. The estimate of an expected odds ratio of 1.8 was based on the following assumptions: *(a)* for 24 years, women aged 60 years (median age of our study population) were exposed to atmospheric radon levels of 10.7 pCi/L vs. 1.4 pCi/L; *(b)* exposures at ages 55–59, 45–54, and 36–44 years would result in increases per WLM in the risk of lung cancer of 0%, 3%, and 1.5%, respectively *(2);* and *(c)* home exposure to 5 pCi/L for 1 year is approximately equal to 1 WLM.

The observed odds ratio for the group exposed to >=8.0 pCi/L was actually below 1.0 and had an upper confidence limit of 1.3. These values suggest that, if our exposure measurements are correct, the risk assessment models may overestimate the effect of household radon in Shenyang.

Alternatively, the assumptions for converting picocurie per liter measurements to WLM may have been incorrect. The conversion generally used assumes that the equilibrium fraction (adjustment to convert picocune per liter measurements of radon gas to WL concentrations of radon-daughter products) is 50% and that 75% of an individual's time is spent at home. At equilibrium, the rate of radioactive decay of radon equals the rate of decay of the radon-daughter products. Alpha-track detectors primarily measure radon concentrations and not daughter product decays. Equilibrium, however, seldom exists, and an adjustment must be made to convert radon measurements in picocuries per liter to WL radon-daughter concentrations. Similarly, to estimate WLM exposure from radon daughters, the amount of time spent at home must be estimated.

Assumptions of different equilibrium fractions and different percentages of time spent at home can lead to a wide range of WLM estimates. For example, it has been suggested that the equilibrium fraction might be as low as 20% for residential settings *(26),* and that the time many persons spend at home might be as low as 65%.

If these alternate assumptions are used, our estimate of the 24-year exposure difference between the high-exposure and low-exposure groups would be reduced from 44 to 15 WLM. As a result, the associated power to detect an effect would be reduced accordingly. In fact, the expected excess of 30% based on such revised models would be within the confidence limits of our data. If these revised assumptions have some validity, then estimates we and others have made of cumulative lung exposure to radon in the home are too high. Thus, investigators of health effects of indoor radon would be even harder pressed to detect radiation risks, and current estimates of radon-induced lung cancer risk in the general population would be much too high.

Conclusions

In summary, this case–control study of lung cancer in a stable population in northern China revealed no evidence of an overall increased risk among women living in homes determined to have high levels of radon. However, caution must be exercised in interpreting these negative results, particularly in view of the potentially confounding influence of indoor pollution in this area. Nevertheless, the data suggest that exposure–response relationships at levels typical of indoor home exposure may not be as steep as suggested by risk models from miner data.

In addition, the excess risks of lung cancer predicted at radon doses near and above 4 pCi/L, which is the remedial action level recommended by the US Environmental Protection Agency, may be too high. The moderate association of radon with small cell cancers is interesting, however, since there is a predilection for underground miners to develop this type of lung cancer. Further epidemiologic studies in different population groups will be needed, with pooled analyses when possible, to clarify the impact of indoor radon on the risk of lung cancer.

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