1993-54

TOWARD RESOLVING THE RADON CONTROVERSY: A NEW APPROACH *

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ABSTRACT

To aid policy makers and residents, the Washington State Department of Health (DOH) is working to evaluate the lowest exposure range at which excess lung cancers are observed. The analytical method used is a departure from the commonly used risk assessments that extrapolate from high to low exposure and will be used to estimate the number of Washington residents at risk. Because most of the residential exposures in Washington fall below the observed health effects range, additional analysis is used to examine the data.

INTRODUCTION

In a departure from the common use of the miner studies, the analysis in this study takes a narrower course. Rather than extrapolate from high mine exposures to low residential exposures, the analysis relies on a miner study with a pattern of exposure that closely resembles a pattern of exposure that occurs in homes. The analysis does, however, extrapolate from mine to home conditions by using the dosimetry research findings of the National Research Council's companion volume to the BEIR IV report. The study also relies on the Surgeon General's report on the health effects of smoking and radon. It takes a traditional epidemiological approach to the residential radon studies; recognition of the limitations of the individual studies and acknowledgement of the collective strength of the research to identify trends and to offer a weight-of-evidence opinion. The study also discusses the radon issue in the larger context of radiation protection, and presents the guidance of national and international authorities.

MINER VERSUS RESIDENTIAL STUDIES

The miner studies demonstrate conclusively that radon causes lung cancer, and does so independently of smoking and other pollutants. No longer a matter of controversy, this finding is the cornerstone in the foundation of knowledge about radon. The scientific consensus around this finding is testimony to the strength and consistency of the evidence from these studies.

The results of the residential radon studies, on the other hand, are mixed. Some find no indoor radon-lung cancer association, some find a positive association, some negative. Both the ecological and case-control studies have limitations. The ecological studies can neither prove nor disprove a causal association between a variable and an outcome. The case-control studies are stronger, but many of the radon studies use proxies in place of direct radon measurements, fail to control for confounding factors, and have low statistical power from using small numbers of cases and controls. Two of the more recent studies, Pershagen 92 and Axelson 88, overcome some of these weaknesses, but cannot definitively establish an indoor radon-lung cancer association either separately or together. If the findings of the other studies all supported the Pershagen and Axelson findings, the weight of evidence would be convincing, but the results of the other studies are mixed, and the weight of evidence from the residential studies is inconclusive.

* This paper is an excerpt from the August 24, 1993 draft of Radon in Washington; a comprehensive report by G.C. Hughes. Any questions can be directed to Mr. Hughes at Washington State Department of Health, P.O. Box 47827, Olympia, WA 98504-7827, telephone (206) 586-8689.

Considered in combination with the results of the miner studies, the results of the residential studies imply that the lung cancer effects of radon exposure are not particularly large. In situations where the effects are large (the lung cancer effects of smoking, for example), even poorly done studies tend to find the association. The mixed findings of the ecological studies are consistent with the conclusion of a small lung cancer effect because weak risk factors can be overwhelmed by important variables (smoking and mobility, for example). In addition, a residential study with a finding of a negative association cannot meet the epidemiological test of biological plausibility: in light of the central finding of the miner studies, a negative association makes no sense.

Some residential exposures are higher than some of the lower mine exposures, and an examination of this range of overlapping exposures provides an opportunity to estimate the lung cancer effects of residential radon without reliance on high-to-low exposure extrapolations. Swedish iron miners studied by Radford and Renard accumulated 31 WLM of exposure over 20 years, and experienced 2.4 times the number of expected lung cancer cases. The comparable residential exposures, as adjusted for the rate of occupancy and for the dosimetric risk extrapolation (K) factor, are roughly 10 pCi/l over 20 years. The inference of a comparable lung cancer effect for residents exposed at this level, i.e., 2.4 times the base lung cancer rate, appears to be reasonable. The miner literature has a collective strength that supports the Radford and Renard study, and reinforces the reliability of these mine-home exposure comparisons.

A NEW APPLICATION OF THE MINER STUDIES

The validity of high-to-low exposure extrapolations is an open question in the fields of toxicology and radiation protection. Based on the view that such extrapolations are a method of last resort, this study develops an alternative analysis. This analysis recognizes the importance of the pattern of exposure, relies on the principles of toxicology, epidemiology, and radiation protection, and provides a reliable basis for the development of public health policy regarding residential radon.

As a rule, mine exposures differ from residential exposures both in dose rate and in length of exposure: the dose rate is usually higher, the duration of exposure is usually shorter. The higher dose rate compensates for the shorter period of exposure so that exposures, expressed in Working Level Months (WLM), are generally higher in mines than in residences. Some residential exposures, however, are higher than some of the lower mine exposures, and an examination of this range of overlapping exposures provides new insights into the health effects of residential radon.

Rather than use extrapolations from the higher mine exposures to infer a lung cancer risk in residential conditions, this study considers this range of overlapping exposures. The analysis presented here examines a miner study with pattern of exposure similar to residential exposures, and carefully develops the basis for mine-home comparisons. It applies the comparative dosimetry work of the National Academy of Sciences to adjust for differences between mines and residences, and for differences between miners and the general population. It also takes into account the percentage of time people spend in their homes. The results, while more limited than those of conventional studies, establish a more reliable foundation for the development of public health policy.

The miner study of interest appears in the New England Journal of Medicine. The study authors, Radford and Renard, report an excess risk of lung cancer for Swedish iron miners exposed to low concentrations of radon progeny over a long period of time (Radford and Renard 84). According to the authors:

* the average exposure period for miners in this study is 19.5 years;
* the lowest exposure category with an excess risk of lung cancer is 0-49 WLM; and
* the mean of the 0-49 WLM exposure category is 26.8 WLM.

Other miner studies report excess lung cancer incidence at lower cumulative exposures (Howe 86; Sevc 88), but the exposure periods for the miners in these studies are much shorter. The advantage of the Radford and Renard study lies in the combination of the low exposures and the long exposure period.

As is the case in most radon studies, miner or residential, the exposure data in the Radford and Renard study are somewhat limited. Actual radon measurements are available for only part of the exposure period. For the period prior to the measurements, the authors reconstruct exposures on the basis of the measurements together with knowledge of the natural and mechanical ventilation of the mines, and an analysis of historical quartz dust concentrations. The authors acknowledge the uncertainty of the exposure data, and suggest that, "...average exposures are probably accurate to ± 30 percent" (Radford and Renard 84).

In comparing the miners to the control group, the authors account for the miners' residential radon exposures: the miners and the controls experience similar residential radon levels. The miners' residential exposures nevertheless warrant further consideration because those exposures contribute both to overall exposure and to risk. Radford and Renard report that a small survey of houses in the region found a range of indoor radon levels of 0.4 to 6.0 pCi/l. At an occupancy rate of 60 percent, and with a 0.7 K factor, these radon levels would accumulate to 0.9 to 13 Working Level Months (WLM) over a 20-year period.

The authors warn that, "Because of the relatively low doses resulting from mining, the contribution of potentially variable exposures at home could modify total radon-daughter exposures at least to some extent" (Radford and Renard 84). An average of 2 pCi/l was calculated and used as the representative indoor radon level for the region. At a 60 percent occupancy rate and with a 0.7 K factor, the 2 pCi/l average radon level would contribute an additional 4 WLMs to the miners' total exposure over a 20-year period.

The National Institute for Occupational Safety and Health's (NIOSH) review of miner studies notes the limitations of Radford and Renard's reconstructed exposures, but concludes that, "...the iron miners as a group probably received very low average exposures compared to uranium miners" (NIOSH 87). The NIOSH review points out that the potential for error due to variations in concentrations is less at the lower radon concentrations found in Swedish iron mines than at the higher concentrations found elsewhere. The BEIR IV committee used the exposure values calculated by Radford and Renard (NRC 88), and, in his review of the literature, a researcher from Yale wrote, "The best of the Swedish studies is the one by Radford and Renard, which is notable for its long follow-up, the low average exposure, and the high LC risk per WLM" (Archer 88).

The only serious challenge to the Radford and Renard study comes from a report by Swent and Chambers done for the American Mining Congress. The authors question the reconstructed exposure values, and suggest that Radford and Renard underestimate the exposures received by the miners. This in turn leads to an overestimation of the risks. The Swent and Chambers report is an industry study, was not subject to peer review, and is not available through normal research channels. The Swent and Chambers criticisms do not compromise the acceptability of Radford and Renard's exposure estimates.

The Radford and Renard study has other strengths in addition to its unique pattern of exposure. The authors control adequately for smoking, and they consider other mine pollutants such as silica, diesel exhaust, arsenic, chromium, nickel, and asbestos. This study also has the exceptionally long follow-up period of 44 years, a critical element in assessing lung cancer incidence at low radon exposures.

One implication of the long (5- to 30-year) lag time between exposure to radon and diagnosis of lung cancer is that the follow-up period in a study must be long enough for all of the cancer cases to develop. Studies of Czechoslovak uranium miners demonstrate how the length of the follow-up period can affect the findings. A 1976 study followed a group of Czech miners from the beginning of their work through 1973, a period of up to 25 years, and found that the lowest exposure category with a statistically significant excess of lung cancer cases was 100-149 WLM (Sevc 76). A later study of the same miners followed the group through 1980, seven additional years, and found that the lowest exposure category with a statistically significant excess of lung cancer cases was 50-99 WLM

(Sevc 88). These findings suggest the importance of a long follow-up period, and that an insufficient follow-up period may obscure the real incidence of cancer at low exposures.

The NIOSH review, in a discussion of the lowest radon exposure ranges associated with excess lung cancer cases, supports this conclusion. According to NIOSH, "A longer follow-up period...may reveal an association between excess lung cancer mortality and radon progeny at lower cumulative exposures" (NIOSH 87). Shorter follow-up periods notwithstanding, some miner studies lend credibility to the Radford and Renard findings by reporting excess lung cancer cases at similar ranges of exposure. In addition to the Czech study cited above, a study of Ontario miners, for example, finds excess lung cancer cases at the 40-90 WLM exposure range with only 18 years of follow-up (NIOSH 87; Muller 85). Similarly, a study of Italian pyrite miners finds excess lung cancer cases in the 24-60 WLM range (Battista 88).

In summary, the Radford and Renard study, in combination with the other miner studies, provides a sound basis for a comparison with residential exposures. The central question for the analysis is this: what residential radon levels would result in cumulative exposures equivalent to the Swedish miners' exposures? For convenience in making the comparisons, the 19.5-year miner exposure period is rounded to 20 years, and the mean cumulative miner exposure of 26.8 WLM is rounded to 27 WLM. In addition, the miners' residential radon exposures add 4 WLM, giving a total exposure of 31 WLM. In consideration of these figures, the question becomes this: what residential radon level would result in a cumulative exposure of 31 WLM in 20 years? The answer to this question depends on three variables--the equilibrium factor, the K factor, and the occupancy factor.

The equilibrium factor governs the conversion of radon measurements in pCi/l to radon progeny measurements in working levels (WL). This analysis uses a widely-accepted equilibrium factor value of 0.5. Applying this value to a radon measurement of 4 pCi/l yields a radon progeny measurement of .02 WL.

The K factor accounts for differences in environmental conditions between mines and residences, and for the differences between miners and the general population. The work of the National Research Council's Comparative Dosimetry Committee provides the dosimetric risk extrapolation factor, expressed as K = 0.7. The analysis applies this factor as a multiplier in the calculation of residential exposures in WLM.

The occupancy factor accounts for the exposure time differences between mines and homes. The WLM unit of exposure is based on the normal mine work schedule of 170 hours per month. The percentage of time residents spend indoors in their homes determines their amount of exposure time. This analysis uses the 75 percent occupancy factor that the U.S. Environmental Protection Agency derives from an analysis of occupancy patterns. Residential exposures with a 75 percent occupancy factor add up to 38.6 working months per year, compared to the 12 working months per year for mine exposures. As with the K factor, the analysis applies the occupancy factor as a multiplier in the calculation of residential exposures in WLM.

The application of the values of these three factors yields the residential radon level that results in 31 WLM of exposure in a 20-year period. Working back to the residential radon level: 31 WLM divided by 20 years yields 1.55 WLM per year. The 1.55 WLM per year divided by the 38.6 working months per year occupancy factor and the 0.7 K factor yields .057 WL of radon progeny exposure after accounting for the mine-home differences. Application of the 0.5 equilibrium factor converts this radon progeny exposure of .057 WL to 11.5 pCi/l of radon exposure.

Radford and Renard estimate that their exposure data are accurate to ± 30 percent. This estimate implies an uncertainty range of cumulative exposures from 22 WLM to 40 WLM (based on 31 WLM ± 30 percent). The residential radon levels yielding 22 WLM and 40 WLM over 20 years (applying the same equilibrium, K, and occupancy factor values as above) are 8 pCi/l and 15 pCi/l.

Table 1 gives the cumulative 20-year exposures in WLM for selected residential radon exposures. The radon exposures in pCi/l are converted to radon progeny exposures in WL, and then adjusted by the 75 percent occupancy factor (38.6 working months per year) and the 0.7 K factor.

TABLE 1: CUMULATIVE 20-YEAR RESIDENTIAL EXPOSURES IN WLM
Selected Radon Levels; 75 Percent Occupancy Factor; 0.7 K Factor

Radon Level (pCi/l)	Progeny Level (WL)	Cumulative Exposure (WLM)
2	.01	5.4
4	.02	10.8
6	.03	16.2
8	.04	21.6
10	.05	27.0
11.5	.057	30.8
18	.09	48.6
20	.10	54.0

The concentrations of radon in any environment vary widely over time and among specific locations. No one, whether at home or in a mine, receives a constant dose from an unvarying concentration. This variability in radon concentrations over time and place implies that strictly equivalent exposures do not occur under natural conditions.

In the mine-home comparisons here, the cumulative residential exposures are not strictly equivalent to the cumulative mine exposures. While both exposures add up to 31 WLM over 20 years, the patterns of exposure within the 20-year period are somewhat different. The residential exposures, at a 75 percent occupancy rate, accumulate at 38.6 working months per year versus 12 working months per year for the miners.

This difference implies an offsetting difference; the dose rate for miners must be commensurately higher than the dose rate for residents, all else being equal. The application of the K factor, however, means that all else is not equal, but rather that the residential exposures are reduced by 30 percent to make them comparable to the mine exposures; 1 WLM of mine exposure equals 0.7 WLM of residential exposure. The occupancy and K factor adjustments notwithstanding, and in consideration of the 20-year exposure period, the comparison of the residential exposures to the mine exposures appears to be valid.

This comparison of residential exposures to those of the Swedish iron miners indicates that exposure to an indoor radon level of 11.5 pCi/l at a 75 percent occupancy rate for 20 years entails an elevated risk of lung cancer. Radford and Renard find that the number of lung cancer cases for the miners in this exposure category was 2.4 times the number of expected cases. Exposures to higher radon levels over a similar period of time would in all likelihood pose relatively higher risks of lung cancer.

On the other hand, this analysis has limitations. It offers no direct evidence of an association between lung cancer and radon levels below 11.5 pCi/l. Nor does it certify that higher radon levels (say, 23 pCi/l) over shorter exposure periods (say, 10 years) would yield a risk of lung cancer similar to the 11.5 pCi/l and 20-year exposure pattern. While this analysis does not resolve the entire radon controversy, it does lend credence to the inference that certain patterns of residential radon exposure pose an elevated risk of lung cancer.

The indication of a health risk at residential radon levels of 11.5 pCi/l implies more precise knowledge than the analysis can claim. The significant figures are artifacts of the calculations rather than expressions of knowledge, and rounding the 11.5 pCi/l down to 10 pCi/l seems an appropriate adjustment. Rounding down is conservative in terms of protecting the public health, and the 10 pCi/l figure may more accurately reflects the level of knowledge achieved by the analysis.

PROJECTIONS OF WASHINGTON RESIDENTS AT RISK

The health effects analysis indicates a health risk at residential radon levels of ≥10 pCi/l. The implications of this finding for Washington residents revolve around answers to the following questions:

* What percentage of Washington houses have radon levels greater than or equal to 10 pCi/l?
* How many Washington residents are at risk?
* How are the high-radon houses (and their residents) distributed throughout the state?

Approximately 106,000 Washington residents are at risk at the ≥ 10 pCi/l radon level. Table 2 provides a region-by-region breakdown.

TABLE 2: PROJECTIONS OF WASHINGTON RESIDENTS AT RISK
Radon Levels ≥ 10 pCi/l

Region	Population	S-F H Res.	% ≥ 10 pCi/l	Res. at Risk
1 (NE)	530,699	382,000	19.9	76,000
2 (SW)	1,336,595	962,000	2.0	19,000
3 (SE)	480,166	346,000	3.1	11,000
4 (NW)	2,519,232	1,814,000	0.0	0
State Total				106,000

S-F H Res. = Single-family home residents = 72% of Population

Res. at Risk = Residents at risk = S-F H Res. x % ≥ 10 pCi/l

PUBLIC HEALTH STRATEGIES: RADON TESTING AND MITIGATION

Testing and mitigation are the essential elements in any effort to control exposures to radon in residences. The DOH radon strategies concentrate on these two areas, and recognize that the financial responsibility for radon testing and mitigation rests with homeowners. The strategies reflect a knowledge of radon characteristics, including the health effects of radon, and an understanding of the geographic distribution of indoor radon throughout the state.

<u>Testing</u>

The only way to know the radon level in a home is to test. High radon levels can occur in homes even in low radon potential areas. Anyone concerned about the radon level in their home should test.

The state building code requires local building departments to provide radon monitors for new homes completed between July 1, 1992, and June 30, 1995. The laboratory analysis and postage are prepaid. Anyone receiving a free radon monitor with their new home should test.

The geographic analysis identifies Ferry, Okanogan, Pend Oreille, Skamania, Spokane, and Stevens Counties as having high radon potential. Everyone living in these counties, in residences below the third floor, should test.

The geographic analysis identifies Grant, Lincoln, and Wahkiakum Counties as having moderate radon potential. People living in these counties should consider testing. Their foundation type, how they use their basement if they have one, the number and ages of the members of their household, and their occupancy rate are all relevant to the testing decision.

<u>Mitigation</u>

Homeowners should mitigate their homes to reduce their radon levels whenever the reduction in risk justifies the cost of the reduction. The relevant considerations for this calculation include: the pre- and post-mitigation radon levels; the number of persons in the household; the age, smoking status, and occupancy rate of each resident; and the estimated costs of the mitigation.

The DOH strongly urges homeowners with residential radon levels $\geq$ 10 pCi/l to mitigate.

The DOH strongly urges homeowners with residential radon levels of 4 to 10 pCi/l to consider mitigating their homes. This guidance is consistent with standard radiation protection advice that individuals should avoid unnecessary exposures to ionizing radiation, and with numerous analyses of the health effects of radon. Homeowners with radon levels of 4 to 10 pCi/l should compare the reduction in risk to the costs of mitigation, and decide for themselves whether or not to mitigate.

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