

Living with Radon and Uncertainty
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Introduction

Lung cancer is the second leading cause of death in the United States, heart disease is the first. In 1990 an estimated 142,000 will die from lung cancer and approximately 157,000 new cases will be reported.¹ Of the latter, only 20,000 are expected to survive beyond five years. For all practical purposes lung cancer is 100% fatal.

The Environmental Protection Agency has predicted that 8,400 - 43,000 lung cancer deaths each year can be attributed to radon with their best estimate at 21,600.² If the EPA's estimate of 21,600 is correct, radon is responsible for 15% of lung cancer deaths. It would also be responsible for approximately the same number of deaths as homicides, the various diseases of infancy, and leukemia.³ Radon has also been cited in several recent reports as a possible cause of leukemia, cancer of the kidney and melanoma.^{4,5,6} It is no wonder that radon is widely considered the most hazardous indoor air pollutant.

Nevertheless, many do not share this view, and argue that the risks are exaggerated.^{7,8} Nor are these skeptics easily dismissed - more than one study has reported a negative correlation between radon and lung cancer!^{9,10}

The purpose of this report is straightforward: determine if it can reasonably be concluded that exposure to environmental levels of radon is a serious health threat to the public.

Radon - a cause of leukemia, kidney cancer, and melanoma?

Several recent reports in The Lancet, a British medical journal, have indicated that radon levels in the home correlate with the incidence of acute myeloid leukemia, cancer of the kidney, and melanoma.^{4,5,6} According to one estimate, radon was responsible for 13-25% of acute myeloid leukemias worldwide and up to 72% of melanomas in the United Kingdom.⁵

The authors hypothesize that the increased rate of leukemia results from exposures to stem cells in the bone marrow. They propose that the inhaled radon is absorbed into the blood and then accumulated in fat cells of the bone marrow. The dose received by the hematopoietic tissue in close proximity to the fat cells is assumed to manifest itself as leukemia.

The increased incidence of kidney cancer is attributed to an accumulation of the long-lived radon daughters in the kidney. Other studies have observed similar effects: an increase in renal disease has been reported in two uranium miner cohorts¹¹ and cancer of the kidney in rats has resulted from exposure to radon.¹²

Accumulation of the short lived radon daughters on the skin is the proposed explanation for the increase in melanomas. Although not statistically significant, an increased incidence of melanoma were reported for two cohorts of uranium miners.¹¹ Studies with rats have also observed increases in skin cancer.¹²

Nevertheless, for the following reasons these reports linking environmental levels of radon to leukemia, kidney cancer and melanoma should be treated with caution.

1. An increase in the incidence of leukemia was not observed in the underground miner studies. If an increase can be detected among the public, surely it would be observed among the miners.
2. Although kidney disease has been reported among uranium miners, cancer of the kidney has not. Again, if cancer is not associated with occupational exposures, why should it be expected at environmental levels?
3. As far as the melanomas are concerned, the underground miner studies don't provide much support - the few reported increases of melanomas were not statistically significant. Furthermore, we would expect an increased incidence of nasal cancers to be more likely than melanomas,

since substantially more radon daughter activity will deposit in the nasal passageways than on the skin. Yet an increase in nasal cancer is not observed, even among the miners.

4. Surprisingly these studies did not observe an association between lung cancer and exposure to radon. These are not the only studies failing to see such a relationship. Nevertheless it is hard to imagine radon exposures increasing the incidence of leukemia but not that of lung cancer since the absorbed dose to the lung will be much greater than that to the hematopoietic tissue of the bone marrow.
5. The studies described in the Lancet are ecological investigations and provide the weakest form of epidemiological evidence (this will be discussed in more detail later on).

To conclude, the evidence linking radon to leukemia, cancer of the kidney and melanoma seems far too weak to support the proposition that radon is a significant health hazard.

Radon and lung cancer - epidemiological investigations
at environmental concentrations

If we are going to obtain convincing evidence that radon is a significant threat to the public health, it is going to have to come from properly designed epidemiological studies involving

exposures at environmental (i.e. low) levels. When the risks are derived from exposures at other than the environmental levels to which the public is exposed, questions will persist about the validity of the conclusions. At the same time, the study design must be able to account for confounding factors that may affect the lung cancer rate.

Epidemiological studies are being performed in two ways. The first is the ecological study in which cancer rates in various counties, states, or countries are determined along with the average indoor radon concentrations. Cancer rates are then correlated with the radon levels. A positive correlation is suggestive of a cause and effect relationship. The second, more difficult and vastly preferred approach is the case-control study. In such a study, individuals who have died of lung cancer, or been diagnosed with it, are identified. For each of these cases, a matching control individual is identified without lung cancer. In every other way the cases and controls must be as similar as possible. Then by one means or another, the radon exposures of the two groups are estimated, compared and the correlation determined.

The following discussion is based upon a review by Samet¹⁰ containing useful summaries of the major ecological and case-control studies performed up to 1988 and several studies published since that date.

1. Ecological studies

Samet's review clearly reveals the contradictory nature of the results of the ecological (descriptive) studies: sometimes an increase in lung cancer is correlated with high radon concentrations, sometimes it is not. Three studies appearing since Samet's review observed no increased risk of lung cancer in regions with elevated radon concentrations.^{5,9,13}

Nevertheless, evidence from these ecological studies would be weak even if the results were in complete agreement. This type of investigation does not determine the radon exposures of the individuals who actually develop lung cancer - only the average radon concentrations in the geographic region where the lung cancer victim dies is known. More importantly, these studies fail to properly account for confounding factors such as smoking. For example, we might expect to see lower rates of lung cancer in predominantly rural areas where fewer people smoke. At the same time, such regions may have higher average indoor radon concentrations than highly urbanized areas due to a combination of home construction characteristics and meteorology. In other words, we might observe an increase in lung cancer due to smoking in urban areas, but report instead a negative correlation between lung cancer and radon. A cogent critique of ecological studies by Conrath is recommended as an introduction to the subject.¹⁴

In summary, no firm conclusions regarding the risk of lung cancer due to radon exposures can be drawn from the rather weak and contradictory evidence of the ecological investigations.

2. Case-control Studies

Case-control studies are our best hope for unequivocally determining the relationship between exposures to environmental levels of radon and lung cancer. Unfortunately, the results of the case-control studies performed to date have been as contradictory as the ecological studies. In looking for an explanation, two major limitations of the studies stand out. First of all, they have generally been small scale investigations - most involved fewer than 40 cases. Secondly, the majority of these studies have not actually measured the radon exposures.¹⁰ Instead, the radon concentrations were estimated according to the construction characteristics of the homes in which the cases and controls had lived. This defeats one of the major advantages of the case-control study: the ability to accurately determine the radon exposures for each individual in the study.

Since the review by Samet, three large scale case-control studies have been published, one from Sweden,¹⁵ another from New Jersey,¹⁶ and the third from China.¹⁷

In the Swedish investigation, Svennson et al. observed a positive correlation between the incidence of lung cancer and the

estimated radon exposures.¹⁵ Slightly over 200 cases and 400 controls were studied. Once again however, the primary means for determining radon exposures was evaluating the construction characteristics of the residences in which the study groups had lived. The Swedish estimates of radon exposures are less accurate than those of the New Jersey and Chinese studies which performed year long alpha track measurements for each individual.

The New Jersey case-control study involved 433 cases and 402 controls (all women).¹⁶ The results show a statistically significant increase in lung cancer risk with increasing radon concentrations in the home. Although an increase in risk with cumulative exposure (in pCi-years) was observed, it was not significant. The authors concluded that the current EPA guideline of 4 pCi/l was appropriate and that radon exposures should be kept at the lowest feasible levels.

In a similar study of Chinese women, the National Cancer Institute investigated the radon exposures of 308 cases and 356 controls.¹⁷ The investigators observed "no evidence of an overall increased risk among women living in homes determined to have high levels of radon" and concluded that the EPA's risk estimates at and above the 4 pCi/l action level "may be too high".

Thus, the results and conclusions of the two best case-control studies released to date appear to be at odds. Whatever the results, the next few years will be most interesting as more

studies of this kind are completed and published. An excellent overview of the major case-control studies in progress can be found in the proceedings of the International Workshop on Residential Radon Epidemiology.¹⁸

Radon and lung cancer - epidemiological investigations at occupational concentrations

Because the studies involving environmental exposures to radon are inconclusive, the risk to the public must be derived from the observed risk to the occupationally (i.e. highly) exposed underground miners. The latter represents the only other large body of human data available.

All the miner studies share a number of problems which introduce substantial uncertainty into the derived risk estimates. Some of the more serious problems include: the large uncertainties in estimates of the cumulative exposures of the miners; the miner's smoking histories are known for only a few cohorts; the confounding effects of uranium ore dust, diesel engine exhaust, explosive residues and other pollutants in the mine air; and the miner cohorts only include adult males.

Despite these and other problems, the underground miner studies are unanimous in at least one observation: they all observe an increased incidence of lung cancer as a function of

increasing radon exposure.^{10,11,19,20,21,22} Furthermore, the excess risk estimates observed in these studies are quite similar, falling within the relatively narrow range of 0.5 - 3.0 lung cancers/100 WLM.^{10,24} *

Radon exposures at occupational levels in mice, rats, and dogs have all resulted in increased lung cancer rates and the observed risks are remarkably similar to those in humans.

A number of issues remain to be addressed before the risks to the general public can be estimated. For example, how to treat the combined effects of radon and smoking, the effect of time since exposure, and the age at first exposure has to be decided. Perhaps the most widely accepted risk models are those of the ICRP and BEIR IV (the EPA employs a combination of both). The following discussion will consider these issues and how the ICRP and BEIR IV committee deal with them.

The general consensus is that the combined risk of smoking and exposure to radon is greater than the sum of their individual risks - i.e. the risks are not additive. There is good evidence for this from the uranium miners studies and animal studies as well. Most workers have taken the approach that the risks are multiplicative

Footnote:

* Occupational exposures are commonly expressed in working level months (WLM). Since the risks to the public are derived from those to the miners, it has become common to express the risk to both groups in terms of WLMs. The typical annual exposure to a member of the public is estimated to be ^{0.30} ~~0.20-0.25~~ WLM.

and this assumption is inherent in the models used by the ICRP and BEIR IV to predict the risks to the public. It is an important assumption because treating the interaction as less than multiple could substantially reduce the overall estimated mortality from environmental exposures to radon. Nevertheless some studies suggest that a submultiplicative approach is more appropriate. Although the BEIR IV committee finally adopted a multiplicative model, they also recognized that the submultiplicative model fitted the miner data just as well or even better in some cases.¹¹ Other studies point to an additive relationship and one miner study even reported a decreased risk in smokers!²³

A decrease in the relative risk of lung cancer after exposure has been observed in a number of investigations.^{11,24,25} Indeed, the BEIR IV committee concluded that the evidence was sufficiently strong to incorporate this effect into their risk assessment model. Exposures accumulated more than 15 years prior to a given attained age are assigned one half the risk of an exposure accumulated during the 5 to 15 years immediately prior to that age. However, a reduction in risk related to the time since exposure is not seen with the atomic bomb survivors nor is it observed in all the miner cohort studies. After examining the available data, the ICRP, unlike BEIR IV, chose to assume a constant relative risk model wherein the risk does not change with time following the exposure.²⁰

The ICRP's assumption of a constant relative risk is important because they also assume that greater risks are associated with

exposures to those under twenty years of age. Nevertheless, no significant evidence for this is found in the underground miner studies.¹¹ In a study of Chinese tin miners, the only miner cohort where large numbers began their career before twenty (37% began working before thirteen years of age), no increased risk with early exposures was observed.²⁴ The principle evidence cited by the ICRP comes from studies of the atomic bomb survivors. However it is not clear that the same effect should be expected from the chronic high LET radiation exposures associated with radon and the acute exposures to low LET radiation characteristics of the nuclear explosions.

All things considered, the studies of the underground mining populations provide us with the best evidence that an increased risk of lung cancer is likely to be associated with environmental exposures to radon. While the magnitude of the risks to the public estimated by various organization may differ, this is not surprising. The choice of risk factor and the manner in which the confounding factors are accounted for are matters upon which the evidence permits considerable disagreement.

Extrapolating from miners to the public - is it justified

Is it reasonable to derive the risks to the public from the risks observed among the miners? Not only are the exposures to the

miners higher, they are also of shorter duration than those to the public.

Overall, the evidence seems to warrant it.

First of all, the cumulative exposures to the public are not very different from those known to cause cancer among the miners. A member of the public continuously exposed to 4 pCi/l, the EPA action level, would receive a lifetime cumulative exposure of approximately 50 WLM. Among the uranium miners, an increased risk of lung cancer has been observed with exposures as low as 100 WLM.^{21,22,24} Furthermore, there is evidence which suggests a linear dose-response relationship in the lower exposure ranges.^{11,21} In other words, the risk is likely to be the same for the "low" environmental exposures and in the "high" occupational exposures.

Secondly, the miner studies, and some animal studies as well, tend to indicate that the risk increases as the exposure rate decreases.^{12,26,27} Other things being equal this suggests that the risks from the chronic exposures to the public may be even greater than the relatively acute exposures to the miners. Nevertheless, this effect of dose rate is not seen in all the miner studies and the exposure ranges experienced by the public. Even if this effect does not occur, it simply means the estimated risk to the public is less likely to be underestimated.

Radon and lung cancer - a dosimetric approach

Dosimetry provides a useful alternative to the epidemiological studies for estimating the risks associated with radon exposures. In the following discussion, the dose to the bronchial epithelium of the lung from a cumulative exposure of 1 WLM will be determined. This will be converted into an effective dose equivalent which in turn will be translated into a risk of cancer by the ICRP's risk factor. Note that 1 WLM is only slightly more than what would occur from a one year exposure to the EPA's action level of 4 pCi/l.

The dose delivered to the lining of the lungs will depend on many things, the radon daughters equilibrium, the attached fraction, the size of the particulates, the inhalation rate, the size of the respiratory passageways, the identity and location of the target cells, etc. Taking these variables into account, various dosimetric models have calculated the dose to the bronchial epithelium of the lung to be on the order of 0.5 - 1.0 rad/WLM (5 - 10 mGy/WLM).^{11,20,28} Employing a quality factor for alpha particles of 20, this becomes 10 - 20 rem/WLM (100 - 200 mSv/WLM). With the ICRP's suggested weighting factor of 0.06 for the bronchial epithelium, this translates into a whole body effective dose equivalent of 0.6 - 1.2 rem (6 - 12 mSv). The ICRP's risk factor of $1.65 \times 10^{-4}/\text{rem}^{29}$ would therefore predict $1 - 2 \times 10^{-4}$ lung cancer deaths per WLM.

This estimate, for the most part arrived at on dosimetric grounds, falls at the lower end of the range of risk estimates usually seen in the epidemiological studies of the miners: $1 - 5 \times 10^{-4}$ per WLM.^{11,20,21} The revised risk estimates might result in an approximately three fold increase in the projections of our dosimetric model. This places the dosimetry and epidemiology risk estimates in close agreement. Two separate paths have reached the same conclusion.

Conclusions

Substantial uncertainties plague every attempt to estimate the risks from environmental levels of radon.

Nevertheless the following points can be made with a reasonable degree of confidence.

1. There is no doubt from the epidemiological studies of the miners and the animal studies that exposures to occupational levels of radon increase the risk of lung cancer. In other words, radon is a known carcinogen.
2. There is a substantial body of evidence indicating that it is reasonable to derive the risk to the public from that observed among the occupationally exposed miners.

3. The risk derived from the lung dosimetry falls within the same range as the risks derived from the underground miner studies.
4. These estimated risks are substantial. Whether radon is responsible for the 9000 lung cancer deaths per year predicted by the NCRP or the EPA's estimate of slightly over 20,000, the number is still large.

Even without this evidence, the public's exposure to radon would be a serious concern when evaluated by the conventional yardsticks used in radiation protection.

For example, consider that the EPA's action level of 4pCi/l (a not uncommon indoor concentration in some parts of the country), is above the maximum concentration permitted by the NRC in effluents from a licensed facility. The effective dose equivalent to the body associated with 4 pCi/l concentrations is approximately 600 to 1200 mrem per year. This is above the "old" NRC limit of 500 mrem to the public as well as the "new" value of 100 mrem. Furthermore, the dose to the bronchial epithelium would even be a substantial fraction of the nonstochastic limit for workers.

And yet, none of this is essential to our argument, for we have the central philosophy of radiation protection for guidance: that radiation exposures should be kept as low as reasonably

achievable. If we consider this philosophy important enough to guide our actions in the smallest of facilities, surely it becomes so much more important when the exposed population is numbered in the millions.

In conclusion, by every measure we are obligated to treat radon as a serious health threat. Our professional responsibility to safeguard the public requires us to adopt a cautious approach. Our guiding philosophy leads us to keep radon exposures as low as reasonably achievable. Finally, our review of the evidence convinces us that this is the right decision; we have every reason to believe environmental exposures to radon are a causative factor in the development of lung cancer.

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