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Shelter and Indoor Air in the Twenty-first Century: Radon, Smoking and Lung Cancer Risks

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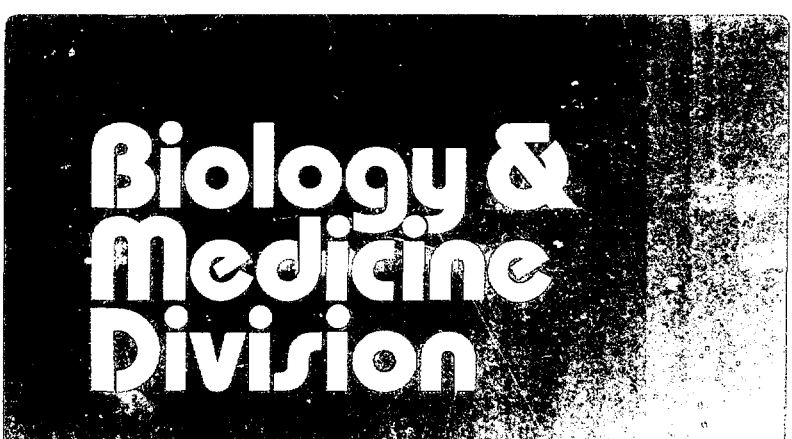

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SHELTER AND INDOOR AIR IN THE TWENTY-FIRST CENTURY

RADON, SMOKING AND LUNG CANCER RISKS[1,2]

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Introduction

My assignment this morning is to discuss with you the quality of the indoor air we breathe and how its condition may affect the public health as we enter the twenty-first century. I think the best thing for me to do is to confine my comments to three problem areas, those of indoor radon, cigarette smoking and lung cancer, and how they may be interrelated. I shall address only the risks of lung cancer in exposed populations, how these have been estimated, and the assumptions and uncertainties both in the estimation process and in the assessment of the potential hazard to the health of the public. I shall not attempt an overview of radon and its decay products in indoor air, nor shall I discuss sources and transport processes, characteristics and behavior of radon decay products, or controlling indoor exposures. My comments deal solely with the basis for health concerns.

Radon and Its Progeny

The terrestrial radionuclide of increasing importance to public health is radon-222, a noble gas and a decay product of radium-226 in the uranium-238 series. This gas emanates from the soil and from building materials of terrestrial origin, e.g., stone, bricks, and concrete. It seeps into homes and office buildings and, when ventilation is restricted, may accumulate in concentrations substantially higher than those prevailing outdoors. In response to the recent need to conserve energy in the heating of homes and office buildings, construction methods that sharply restrict ventilation have been introduced. As a result, the control of radon levels in indoor air is becoming increasingly important.

Deep within the soil, radon-222 concentrations can exceed 1000 pCi L^{-1} (37,000 Bq m^{-3}). Outdoor concentrations of radon-222 vary considerably, but average about 0.2 pCi L^{-1} (7.4 Bq m^{-3}) with much higher concentrations at ground level. In terms of concentration of radon progeny, an average value of 0.001 WL is representative for an outdoor radon concentration of 0.1 pCi L^{-1} (3.7 Bq m^{-3}). The major pathway for exposure of members of the general public is through exposure indoors, where on the average 70-80% of the time is spent. Because closed structures do not allow for extensive mixing of air, the concentrations of radon in buildings tend to be higher than outdoor concentrations. Indoor levels are only moderately higher, averaging about 1.5 pCi L^{-1} (55 Bq m^{-3}) and up to 8 pCi L^{-1} (300 Bq m^{-3}) or more, when ventilation is not greatly restricted. These indoor radon concentrations can vary widely from the ambient air outdoor value to values that are a few thousand times higher. On the average, the level of indoor radon progeny is reported by the NCRP to be about 0.004 WL (0.4 pCi L^{-1} or 15 Bq m^{-3}). In contrast, radon concentrations of 100 pCi L^{-1} (3700 Bq m^{-3}) or more have been measured in some older homes and in recently constructed homes designed to limit ventilation as far as possible. These can be far greater than levels measured in many uranium mines.

The tissues at risk from exposure to radon and its progeny include the surfaces of the bronchi, segmental bronchioles, and alveolar membranes. These tissues are exposed primarily to radon daughters, e.g., polonium-218, which attach themselves to dust particles and, when inhaled, deposit themselves within the respiratory system at locations influenced by particle size. The epithelium of alveoli receives an estimated dose equivalent of approximately 0.5 rem y^{-1} (5 mSv y^{-1}) when radon concentrations in air are 1 pCi L^{-1} (37 Bq m^{-3}). The dose equivalent to the segmental bronchioles may be

approximately 5 times higher.

Thus, the important tissue is the bronchial epithelium which is the site of most lung cancers thought to be induced by radiation. The major contributors to the alpha-radiation exposure are the short-lived decay products of radon, measurements of which show an apparent log-normal distribution of concentrations in indoor air. For smokers, the additional exposure to the lungs from naturally occurring radionuclides in tobacco products increases the dose equivalent to the bronchial epithelium considerably.

Human Populations at Risk

Current scientific reports concentrate on the health outcomes due to exposure to radon and its progeny, primarily because of a need for a comprehensive characterization of the lung cancer risk associated with exposure to radon and its short-lived daughters in indoor domestic environments. Estimation of lung cancer risk appears to be best derived from epidemiological surveys of underground miners throughout the world who breathe widely-differing levels of radon-222 progeny. Calculations based on dosimetric models of the respiratory tract are complex, and values are based largely on the location of the target cells in the bronchial epithelium, the physiological processes involved in the variable dosimetry, and uncertainties introduced by numerous confounding risk factors, such as smoking. All of the epidemiological surveys are presently in progress, the human data on lung cancer induction by radon progeny are limited, none is completed, and the person-years of follow-up are still relatively small, so that until a sufficient number of the study populations have died, most in the next century, the lifetime carcinogenic risks of alpha-radiation exposure remain uncertain.

Permissible concentrations of radon progeny in air can be derived

mathematically by calculating the concentrations in the tissues. The mathematical procedures are quite straightforward; it is the fundamental and physiological assumptions that have proved difficult. It is for these reasons that the need for guidance on protection from the potential health hazards of radon and its daughter products is of current and future concern. For a considerable period, such guidance has been directed primarily to those occupationally exposed in the workplace, as for example, uranium miners. Now, other groups of persons are being considered, and their circumstances differ from those occupationally exposed. We now include the general population, pregnant women, children, and persons who suffer from health conditions that might render them more sensitive to radiation injury. Furthermore, the biological assumptions, mathematical models, and radiation dosimetry are uncertain; following deposition of the radionuclide within the body, the radiation exposure usually has a complex time pattern with varying distribution, and the actual dose and dose rate in the tissue is often inadequately known.

Estimation of Radon-Induced Lung Cancer Risk

Numerous studies of underground miners exposed to radon daughters in the air of mines have shown an increased risk of lung cancer in comparison with nonexposed populations[1]. Laboratory animals exposed to radon daughters also develop lung cancer. There is abundant epidemiological and experimental data to establish the carcinogenicity of radon progeny[1-6]. These observations are of considerable importance because uranium, from which radon and its progeny

arise, is ubiquitous in the earth's crust, and radon in indoor environments can reach relatively high levels. Nevertheless, while the carcinogenicity of radon daughters is established and the hazards of high levels of exposure during mining is well recognized, the risks of exposure to lower levels of radon progeny have not yet been adequately characterized. However, risk estimates of the health outcomes of lower levels of exposure are needed to address the potential health effects of radon and radon daughters in homes and to determine acceptable levels of exposure in occupational environments.

Two approaches are currently used to characterize the lung cancer risks of radon daughter exposure. First are mathematical representations of the respiratory tract that model radiation doses to target cells. Second are epidemiological investigations of exposed populations, mainly underground miners. The dosimetric approach provides estimates of lung cancer risks of radon daughter exposure that are based specifically on modelling the radon-daughter dose to target cells. A number of different dosimetric models have thus far been developed; all require certain relevant assumptions, some not subject to direct verification, concerning the deposition of radon daughters in the respiratory tract and the type, nature and location of the target cells for cancer induction. Because of these assumptions, the uncertainties, and the technical difficulties encountered in this approach, it appears prudent not to use dosimetric models solely for calculating the lung cancer risk estimates. However, the dosimetric approach is of considerable value, and the results of such dose-effect models are used to extrapolate lung cancer risk coefficients derived from the epidemiological studies of occupational exposure of the underground miners to the general population in indoor domestic environments.

The use of available epidemiological data has advantages because the

studies of radon-daughter exposed miners provide a direct assessment of human health effects. While each investigation has limitations, the approach of a combined analysis of the major data sets permits a comprehensive assessment of the lung cancer risks of radon daughter exposure and of factors influencing the risk of exposure. In analyzing original data sets, a descriptive analytical approach may be used rather than using statistical methods based on conceptual models of carcinogenesis or radiation (dose-reponse) effects. In the current 1988 BEIR IV[1] Report, the National Research Council Committee obtained primary data sets from four of the principal and most complete epidemiological studies of radon-exposed underground miners (the Ontario uranium miners, the Saskatchewan uranium miners at Beaverlodge, the Swedish iron miners at Malmberg, and the Colorado Plateau uranium miners) and developed risk models for lung cancer derived from its own formal statistical analyses.

The follow-up experience of the groups analyzed totals over 400,000 person years and includes 458 lung cancer deaths (Table 1). There are important differences among the four studies including the duration of follow-up, the exposure rate, and the degree of uncertainty and potential biases in the estimated exposures. These factors were evaluated extensively and were examined to the extent possible in the epidemiological analysis.

Using statistical regression techniques appropriate for survival time data, the risk or probability of dying of lung cancer due to radon daughter exposure in the combined cohorts and in the absence of smoking may be best described by a complex time-since-exposure statistical model. In this time-since-exposure relative risk model, although simple in its mathematical formulation, the excess relative risk varies with time since exposure rather than remaining constant and depends on age at risk. This expression, therefore, is a departure from most previous risk models which have assumed that the

TABLE 1

CHARACTERISTICS OF THE FOUR UNDERGROUND MINER GROUPS ANALYZED BY THE BEIR IV COMMITTEE[1]

	Number of workers followed	Average duration of followup (y)	Person-years of followup (PY)
Saskatchewan			
surface	1,580	14	22,120
underground	6,847	14	95,858
Ontario			
surface	570	16	9,120
underground	11,086	19	210,444
Sweden (miners)	1,292	21	27,132
Colorado			
(all)	3,347	25	83,675
≤2000 WLM	2,975	25	74,375

	Average age at end of followup (y)	Average duration of exposure (y)	Average cumulative exposure (WLM)	Number of lung cancer deaths
Saskatchewan				
surface	45	--	--	--
underground	43	3.2	22	65
Ontario				
surface	52	--	--	--
underground	50	3.7	37	87
Sweden (miners)	67	20	98	51
Colorado				
(all)	57	8	822	256
≤2000 WLM	57	7	509	157

Totals: surface 31,240
underground 491,484

relative risk is constant over both age and time. Radon exposures more distant in time have a somewhat lesser impact on the age-specific excess relative risk than more recent exposures. Moreover, the age-specific excess relative risk is higher for younger persons and declines at older ages. The relative risk form provides a simpler description of observed lung cancer risks in the miner cohorts; it requires fewer variables than would an absolute risk form.

Recognition that radon and its daughter products may accumulate to high levels in homes has led to concern about the potential lung cancer risk resulting from exposure to radon progeny in indoor domestic environments. While such risks can be estimated with the derived mathematical expression for excess relative risks, it must be recognized that the epidemiological model is based on data from occupational exposure of underground miners. Several assumptions are required to transfer risk estimates from an occupational setting to the indoor domestic environment: (a) that the epidemiological findings in the underground miners could be extended across the entire lifespan, (b) that cigarette smoking and exposure to radon daughters interact multiplicatively, (c) that exposure to radon progeny increases the risk of lung cancer proportionally to the sex-specific ambient risk of lung cancer due to other causes, and (d) that a unit of radon-daughter exposure yields an equivalent radiation dose to the respiratory tract and to the bronchial epithelium in both occupational and domestic environmental settings. It was concluded that additional data on ventilation rates and aerosol characteristics in mines and homes are needed to address quantitatively the comparative dosimetry of radon daughters in the occupational and domestic environmental settings.

Based on the estimates of excess relative risks per WLM, the unit of exposure to radon progeny, derived from analysis of the four miner cohorts examined, and the assumptions, it is possible to project well into the

twenty-first century, the lung cancer risks, lifetime risks, risk ratios, average lifespans, and average years of life lost, for United States males and females for various exposure rates and durations of exposure, and estimated risks conditional on survival to a particular age and for smokers and nonsmokers of either sex.

These risk projections cover exposure situations of current public health concern. Lifetime exposure to 1 WLM y^{-1} is estimated to increase the number of deaths due to lung cancer by a factor of about 1.5 over the current rate for both males and females in a population having the current prevalence of cigarette-smoking. Occupational exposure to 4 WLM y^{-1} from ages 20 y to 40 y is projected to increase lung cancer deaths in males by a factor of 1.6 over the current rate of this age cohort in the general population. In all of these cases, most of the increased risk occurs to smokers for whom the risk is up to ten times greater than for nonsmokers.

Comparisons of estimates of the lifetime risk of lung cancer mortality due to a lifetime exposure to radon progeny in terms of WLM and alpha-particle dose to the target cells of the bronchial epithelium, made by this and other scientific committees over the past decade yield similar lung cancer risk coefficients (Table 2). It must be remembered, however, that in each of the six studies, the epidemiological data available, the dosimetric and statistical models applied, and the assumptions introduced, were quite different, and with differing and alternative methods of analysis. Nevertheless, the excess lung cancer deaths per million person year WLM range within a factor of about 2 at most.

Table 2. Estimates of lung cancer risk due to exposure to radon progeny

Study	Excess Lung Cancer Deaths/10^6 Person WLM
1988 BEIR IV[1]	350
1987 ICRP[2]	170
1984 NCRP[3]	130
1981 ICRP[4]	150-450
1980 BEIR III[5]	730
1977 UNSCEAR[6]	200-450

The uncertainties that affect the estimates of the lung cancer risk include (a) random and possibly systematic errors in the original data on exposure and lung cancer in the miner populations analyzed by the Committee, (b) inappropriate statistical models for analysis or mispecification of the components of the models, (c) sampling variation, and (d) incorrect description of the interaction between radon daughter exposure and cigarette-smoking. In addition, the actual computed lifetime lung cancer risks and expected years of life-shortening depend on the age-specific disease rates of the referent population, here, the 1980-1984 United States population mortality rates. Projections based on a different referent population would be expected to differ, although the ratio of lifetime risks and years of life lost to ambient values may be more stable across populations.

Review of the literature and analyses of the relevant data do not lead to a conclusive description of the interaction between exposure to radon daughters and cigarette smoking. Several data sets have been analyzed and suggest a multiplicative interaction for risk projections on a relative risk scale. A submultiplicative model is also consistent with the data analyzed. Neither

additive nor subadditive models appear consistent with these data.

Ongoing research in the United States and other countries has provided data on concentrations of radon and radon progeny in homes. These studies have also described the sources of radon and determinants of its concentration. There appears to be a log-normal distribution with very wide variation of levels of radon and radon progeny in U.S. homes, with an average of about 1.5 pCi L^{-3} (55 Bq m^{-3}); about 2% of homes exceed levels of 8 pCi L^{-1} (300 Bq m^{-3}), much greater than permissible levels of 4 pCi L^{-1} (150 Bq m^{-3}) in mines recommended by the Environmental Protection Agency. A few exploratory epidemiological investigations of the lung cancer risk associated with radon daughter exposure in homes have been carried out, but the study populations have been small and the results remain inconclusive. These studies are at present inadequate for the purposes of risk estimation. For this reason, the lung cancer risk projections for the general population can only be based on the epidemiological studies of miners. Estimates of lung cancer risks from studies on miners can be used to estimate the potential lung cancer risk from elevated levels of indoor radon. However, the estimates derived are uncertain, particularly since differences between mining and indoor domestic environments and the interaction between smoking and exposure to radon progeny remain incompletely resolved.

Comparison of Lung Cancer Rates

To provide some perspective of the lung cancer risk due to radon exposure, comparisons might be made with the expected risk in the United States. An estimated 130,000 lung cancer deaths occurred in 1986; 89,000 in males and 44,000 in females. About one death in 20 is due to lung cancer, a lifetime risk

of 5%. It has been estimated that cigarette smoking is responsible for 85% of lung cancers among men and 75% among women, some 83% overall. The lifetime risk of lung cancer for nonsmokers is somewhat less than 1%. Even for the nonsmoker, passive smoking may contribute to this one percent or less; it has been estimated that passive smoking may be a contribuiton to this one percent in U.S. nonsmokers. On average, a smoker's risk is about 10 times that of a nonsmoker.

However, the role of smoking as a confounding factor is still not clear from analyses of the underground miner data, and the effect of smoking on radon risk depends strongly on the type of interaction, whether additive or multiplicative. Accordingly, it is very difficult to determine the precise risk of exposure to indoor radon progeny to the general public in the presence of the more proven causative agent, cigarette smoking. Based on NCRP modeling and risk estimates, the annual number of lung cancer deaths attributable to an average indoor air radon exposure of 0.004 WL in a continuosly exposed population of 240 million is about 7000 y^{-1}, but could be as high as 10,000 y^{-1}. Based on the BEIR IV modeling and risk estimates, the lung cancer deaths attributable to radon progeny exposure are calculated to be higher. In both estimates, the excess deaths are in both smokers and nonsmokers, and include exposure to passive smoke.

A satisfactory method of treating the confounding factor of smoking in lung cancer risk assessment, and in establishing levels for protecting the health of the public has not as yet been developed. Thus, the precise radon-induced lung cancer risk in the nonsmoker is uncertain and the overall effectiveness of mitigating and protective measures remain in doubt. Based on the available information, however, the radon risk to the nonsmoker appears to be much less than has been presently estimated. Protective measures are likely

to be most effective in reducing radon risk to smokers, who are already at very high risk.

Conclusions

The present need to apply lung cancer risk projections from surveys of underground miners to estimate risk to the general population from indoor radon introduces numerous uncertainties and technical difficulties. The domestic environment has not, as yet, been characterized adequately in terms of the variables affecting the dose and risk from radon progeny. Variations in indoor radon levels, alterations of aerosol characteristics, and impacts of smoking and nonsmoking risk factors suggest that health consequences resulting from indoor radon exposures require much more study. There is some wisdom in recommending continuation of epidemiological studies of lung cancer resulting from indoor radon exposure and underground mining surveys provided such studies have sufficient statistical power to quantify any significant differences between the risks in the domestic environmental and occupational settings. This will permit us to assess the magnitude of the potential lung cancer risk to the general public from exposure to radon progeny in indoor domestic environments, and thereby help place into perspective the potential ill-effects of this environmental hazard with those pernicious diseases afflicting our nation's health in the twenty-first century.

References

1. NAS (1988). National Academy of Sciences, The Health Effects of Radon and Other Internally-Deposited Alpha Emitters: BEIR IV. (National Academy Press, Washington, D.C.).
2. ICRP (1987). International Commission on Radiological Protection, Lung Cancer Risk from Indoor Exposure to Radon Daughters. ICRP Publication 50 (Pergamon Press, New York).
3. NCRP (1984). National Council on Radiation Protection and Measurements, Evaluation of Occupational and Environmental Exposures to Radon and Radon Daughters, NCRP Report 78 (National Council on Radiation Protection and Measurements, Bethesda, Maryland).
4. ICRP (1979). International Commission on Radiological Protection, Limits for Intake of Radionuclides by Workers. ICRP Publication 30 (Pergamon Press, New York).
5. NAS (1980). National Academy of Sciences, The Effect on Populations of Exposure to Low Levels of Ionizing Radiation. (National Academy Press, Washington D.C.).
6. UNSCEAR (1977). United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and Effects of Ionizing Radiation (United Nations, New York).

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