PAPER 7[1]

HEALTH EFFECTS OF RADON

Exposure of people to radon has taken on increased interest during the last decade because of the understanding that buildings can serve to trap radon and its daughters, and thereby build up undesirable concentrations of these radioactive elements. Numerous studies of underground miners (often uranium miners) have shown an increased risk of lung cancer in comparison with nonexposed populations. Laboratory animals exposed to radon daughters also develop lung cancer. The abundant epidemiological and experimental data have established the carcinogenicity of radon progeny. Those observations are of considerable importance, because uranium, from which radon and its progeny arise, is ubiquitous in the earth's crust, including coal mines.

Risk estimates of the health effects of long-term exposures at relatively low levels require continued development, especially to address the potential health effects of radon and radon daughters in homes and occupational settings where the exposure levels are less than levels in underground uranium and other metal mines that have been the subject of epidemiological studies.

Two approaches can be used to characterize the lung-cancer risks associated with radon-daughter exposure: mathematical representations of the respiratory tract that model radiation doses to target cells and epidemiological investigation of exposed populations, mainly underground uranium miners. The mathematically-based dosimetric approach provides an estimate of lung-cancer risk related to radon-daughter exposure based specifically on modeling of the dose to target cells. The various dosimetric models all require assumptions, some of which are not subject to direct verification, as to breathing rates; the deposition of radon daughters in the respiratory tract; and the type, nature, and location of the target cells for cancer induction.

The most recent large committee effort drawn together to evaluate this issue was sponsored by the National Research Council. Its committee, known as the BEIR IV (Committee on the Biological Effects of Ionizing Radiation)

[1]Based largely on a working paper by C. Easterly.

chose not to use dosimetric models for calculating lung-cancer risk estimates in their report. The lung-cancer risk estimates for radon-daughter exposure derived by the BEIR IV committee are based solely on epidemiological evidence. However, the results of dose models were used to extrapolate lung-cancer risks derived from the epidemiological studies of underground miners to the general population receiving lesser exposure levels.

The committee preferred a direct epidemiological approach, because the studies of radon-daughter-exposed miners provided a direct assessment of human health effects. This decision coincides with our preferred source of data (i.e., direct estimates of risk based on human data) and thus we have chosen to adapt the BEIR IV results for the fuel cycle externalities study. Although each of the epidemiological studies that the committee assessed has limitations, the approach of a combined analysis of major data sets permitted a comprehensive assessment of the health risks associated with radon-daughter exposure and of other factors that influence the risk, such as age and time since exposure. In analyzing the data, the committee obtained data from four of the principal studies of radon-exposure and developed risk models for lung cancer based on analyses of these data. By means of statistical regression techniques appropriate for survival-time data, the committee found that the probability of dying of lung cancer at age a in the combined cohorts was best described by the following expression:

...the BEIR IV committee obtained data from four of the principal studies of radon-exposure and developed risk models for lung cancer ...

$$r(a) = r_o(a)[1 + 0.025\gamma(a)\{W_1 + 0.5W_2\}],$$

where $r_o(a)$ is the age-specific background lung-cancer mortality rate; $\gamma(a)$ is 1.2 when age a is less than 55 yr, 1.0 when a is 55-64 and 0.4 when a is 65 yr or more; W_1 is Working Level Month (WLM) [a measure of exposure to radon and radon daughters][2] incurred between 5 and 15 yr before this age; and W_2 is WLM incurred 15 yr or more before this age. The above relationship has been derived for underground miners. Measures of exposure

[2]A Working Level (WL) is any combination of short lived radon daughters in 1 liter of air that will result in the ultimate emission of 1.3×10^5 MeV of potential alpha energy. This number was chosen because it is approximately the alpha energy released from the decay of daughters in equilibrium with 100 picocuries of ^{222}Ra. A Working Level Month (WLM) is that exposure resulting from inhalation of air with a concentration of 1 working level of radon daughters for 170 working hours.

for evaluating effects associated with the coal fuel cycle should also be in Working Level Months, or the measures should be convertible to WLM.

In the event that radon and daughter exposures provide significant exposures to surface miners and/or members of the public, in order to more accurately evaluate risk, modifications would be required with respect to the equilibrium ratios of the daughters and the particles onto which the daughters attach and are thereby inspired. Further, several assumptions would be required relative to exposure times and differences in the cohorts. However, because of the effort required to obtain greater accuracy, modifications to the above relationship will not be pursued until evidence is obtained that suggests that exposure to surface miners and/or members of the public makes up approximately 10% of either group's total risk from the coal fuel cycle.

The relationship provided in the equation results in an age-specific lung cancer rate. In order to be useful in the present analysis, this must be converted to lost years of life or to an increase in numbers of cancers. Thus it will be necessary to know the workforce size, typical ages of work, (i.e., age 25-55 yr), and nominal exposure levels (in WLM).

The BEIR IV committee reviewed risk estimates made by other scientific groups, including the National Research Council (the BEIR III report). Comparisons between all epidemiology studies are not possible because of large differences in the populations assumed to be at risk, for example, duration of exposure and smoking prevalence. The BEIR IV results are near the middle of range of risks between the BEIR III (NRC 1980), the UNSCEAR (1977) and the NCRP (1984) reports. The major factor separating the BEIR IV from the BEIR III lifetime risks is that the BEIR IV work is based on a modified relative risk model that takes into account the reduced risk at age 65 or greater and the smaller effectiveness of exposures occurring 15 years or more in the past.

The risk of lung-cancer mortality associated with long-term exposure to radon daughters is a function of the duration of exposure and, because of competing risks of death from other causes, of age as well. A valuable measure of mortality is the number of years of life lost because of exposure, L_o - L_e, where L_o is expected years of life at birth for a nonexposed subject, and L_e is expected years for an exposed subject. Note that L_o - L_e is the average for a population of exposed persons. The number of years of life lost by those who actually die of lung cancer is usually much greater - typically, about 15 yr for males and about 18 yr for females.

The BEIR IV committee has calculated age- and exposure-specific risk measures including L_o - L_e for various magnitudes of annual exposure using the male and female 1980-1984 U.S. mortality rates. Mortality rates based on a specific period in the past can only approximate future rates in a population whose total mortality rates vary over time. Moreover, the age patterns and the relative importance of lung cancer as a cause of death are expected to change as smoking becomes less prevalent.

Lifetime risk of lung cancer and expected years of life lost are related to a specified exposure profile for persons who are followed from birth. Those measures do not, however, provide information about lung-cancer risk after survival to some specified age. Total life expectancy when a person is known to be alive at a given age is greater than that at birth, because the rigors of the intervening years have been survived. The following table (Table 1), prepared by the BEIR IV committee, compares risk measures computed conditionally on survival to specific ages for males in the general population. For this assessment, we chose to use general rates since this does not require additional assumptions relative to smoking habits. The column headed 0 gives baseline values without information on age. Table 1 shows the effects on the years of life lost if exposure were to cease at the conditional age known to be alive. The health benefits of eliminating exposure are seen to be substantial into the middle ages. Table 2 shows the effects on lifetime lung cancer risks (R_e) if exposures were to cease at the conditional age known to be alive. Similar tables have been derived for both sexes for smokers and non-smokers.

Application of the relative risk model to the health assessment for the coal fuel cycle requires several assumptions:

(1) Miners begin work at age 20 and continue working until age 60.

(2) The exposure rate to radon and daughters is between 0.1 and 0.2 WLM/y. [We know of no measurements for radon in surface mines; however, the 0.1 to 0.2 WLM/y should be an upper limit. O'Riordam et al. (1981) report levels of between 0.12 and 0.24 WLM/y in underground coal mines.]

(3) Smoking habits and mortality rates remain the same as during the 1980-84 period.

Given these assumptions, the time since exposure model (Table 1) predicts an average of between 0.03 and 0.07 years of life lost per worker. Alternatively, using Table 2, the lifetime risk is between 0.069 and 0.072. Given that the baseline risk is 0.067, the incremental risk is between 0.002 and 0.005. This means that 2 to 5 lung cancer cases are expected per thousand workers with a work history exposure averaging 0.1 to 0.2 WLM/y over the ages of 20 to 60 years. From the analysis of coal mine labor, it is expected that somewhat less than 200 persons would be required to maintain a reference coal plant. Thus, radon exposure might be expected to result, as an upper limit, in one additional lung cancer case over a 40 year period.

Table 1. Radon exposure: years of life lost (L_o - L_e) to lung cancer for males by age started and age exposure ends[a]

	Age (yr) Exposure Ends								
Age (yr) Started	10	20	30	40	50	60	70	80	110
Exposure Rate = 0.10 WLM/yr									
0	0.01	0.02	0.03	0.04	0.04	0.05	0.05	0.05	0.05
10		0.01	0.02	0.03	0.04	0.04	0.05	0.05	0.05
20			0.01	0.02	0.03	0.03	0.04	0.04	0.04
30				0.01	0.02	0.03	0.03	0.03	0.03
40					0.01	0.02	0.02	0.02	0.02
50						0.01	0.01	0.01	0.01
60							0.00	0.00	0.00
Exposure Rate = 0.20 WLM/yr									
0	0.02	0.03	0.05	0.07	0.09	0.10	0.11	0.11	0.11
10		0.02	0.03	0.05	0.07	0.09	0.09	0.09	0.09
20			0.02	0.04	0.06	0.07	0.07	0.07	0.07
30				0.02	0.04	0.05	0.06	0.06	0.06
40					0.02	0.03	0.04	0.04	0.04
50						0.01	0.02	0.02	0.02
60							0.00	0.01	0.01
Exposure Rate = 0.50 WLM/yr									
0	0.04	0.08	0.13	0.17	0.22	0.26	0.27	0.27	0.27
10		0.04	0.09	0.13	0.18	0.21	0.22	0.23	0.23
20			0.04	0.09	0.14	0.17	0.18	0.18	0.18
30				0.05	0.10	0.13	0.14	0.14	0.14
40					0.05	0.08	0.09	0.09	0.09
50						0.03	0.04	0.05	0.05
60							0.01	0.01	0.01
Exposure Rate = 1.00 WLM/yr									
0	0.08	0.17	0.25	0.35	0.44	0.51	0.53	0.53	0.53
10		0.08	0.17	0.26	0.36	0.42	0.44	0.45	0.45
20			0.09	0.18	0.28	0.34	0.36	0.37	0.37
30				0.09	0.19	0.26	0.28	0.28	0.28
40					0.10	0.16	0.18	0.19	0.19
50						0.06	0.09	0.09	0.09
60							0.02	0.03	0.03

Table 1. (cont'd)

Age (yr) Started	Age (yr) Exposure Ends: 10	20	30	40	50	60	70	80	110
					Exposure Rate = 4.00 WLM/yr				
0	0.33	0.66	0.99	1.35	1.71	1.93	2.00	2.02	2.02
10		0.33	0.67	1.03	1.40	1.63	1.71	1.72	1.72
20			0.34	0.71	1.09	1.32	1.40	1.42	1.41
30				0.38	0.76	1.00	1.08	1.10	1.09
40					0.39	0.64	0.72	0.74	0.74
50						0.26	0.34	0.36	0.35
60							0.09	0.10	0.10
					Exposure Rate = 10.00 WLM/yr				
0	0.82	1.61	2.37	3.18	3.96	4.42	4.56	4.58	4.58
10		0.82	1.63	2.47	3.29	3.78	3.93	3.96	3.95
20			0.84	1.73	2.59	3.11	3.26	3.30	3.29
30				0.93	1.84	2.39	2.55	2.59	2.59
40					0.96	1.55	1.73	1.77	1.76
50						0.63	0.83	0.87	0.86
60							0.21	0.26	0.25

[a]Estimated with the BEIR IV time since exposure model. R_e includes R_o, the baseline risk for males in the 1981-84 U.S. population, 0.067; the expected lifetime of males is 69.7 yr.

Source: Adapted from Committee on the Biological Effects of Ionizing Radiations, Board on Radiation Effects Research, Commission on Life Sciences, National Research Council, 1988. Health Risks of Radon and Other Internally Deposited Alpha-Emitters. BEIR IV. National Academy Press, Washington, D.C.

Table 2. Radon exposure: lifetime risks (R_e) for lung cancer for males by age started and age exposure ends[a]

	Age (yr) Exposure Ends								
Age (yr) Started	10	20	30	40	50	60	70	80	110
Exposure Rate = 0.10 WLM/yr									
0	0.068	0.068	0.069	0.069	0.070	0.071	0.071	0.071	0.071
10		0.068	0.068	0.069	0.070	0.070	0.070	0.070	0.070
20			0.068	0.068	0.069	0.069	0.070	0.070	0.070
30				0.068	0.068	0.069	0.069	0.069	0.069
40					0.068	0.068	0.069	0.069	0.069
50						0.068	0.068	0.068	0.068
60							0.068	0.068	0.068
Exposure Rate = 0.20 WLM/yr									
0	0.068	0.069	0.070	0.072	0.073	0.074	0.074	0.074	0.074
10		0.068	0.069	0.070	0.072	0.073	0.073	0.073	0.073
20			0.068	0.069	0.071	0.072	0.072	0.072	0.072
30				0.068	0.070	0.071	0.071	0.071	0.071
40					0.069	0.070	0.070	0.070	0.070
50						0.068	0.069	0.069	0.069
60							0.068	0.068	0.068
Exposure Rate = 0.50 WLM/yr									
0	0.070	0.072	0.075	0.078	0.081	0.083	0.084	0.085	0.085
10		0.070	0.072	0.075	0.078	0.081	0.082	0.082	0.082
20			0.070	0.073	0.076	0.078	0.079	0.080	0.080
30				0.070	0.073	0.075	0.077	0.077	0.077
40					0.070	0.073	0.074	0.074	0.074
50						0.070	0.071	0.072	0.072
60							0.069	0.069	0.069
Exposure Rate = 1.00 WLM/yr									
0	0.072	0.077	0.083	0.088	0.094	0.098	0.101	0.102	0.102
10		0.072	0.078	0.083	0.089	0.093	0.096	0.097	0.097
20			0.072	0.078	0.084	0.089	0.091	0.092	0.092
30				0.073	0.079	0.083	0.086	0.087	0.087
40					0.073	0.078	0.081	0.082	0.082
50						0.072	0.075	0.076	0.076
60							0.070	0.071	0.071

Table 2. (cont'd)

Age (yr) Started	Age (yr) Exposure Ends: 10	20	30	40	50	60	70	80	110
				Exposure Rate = 4.00 WLM/yr					
0	0.87	0.107	0.126	0.146	0.167	0.183	0.192	0.195	0.195
10		0.087	0.107	0.128	0.149	0.166	0.175	0.178	0.178
20			0.088	0.109	0.131	0.148	0.157	0.160	0.161
30				0.089	0.112	0.130	0.139	0.142	0.143
40					0.091	0.109	0.119	0.122	0.123
50						0.087	0.096	0.100	0.100
60							0.077	0.081	0.082
				Exposure Rate = 10.00 WLM/yr					
0	0.117	0.162	0.206	0.206	0.291	0.323	0.338	0.343	0.344
10		0.117	0.163	0.209	0.255	0.289	0.305	0.311	0.312
20			0.117	0.166	0.216	0.253	0.270	0.276	0.277
30				0.120	0.173	0.213	0.232	0.239	0.240
40					0.125	0.168	0.188	0.196	0.197
50						0.114	0.137	0.145	0.146
60							0.092	0.101	0.102

[a]Estimated with the BEIR IV time since exposure model. R_e includes R_o, the baseline risk for males in the 1981-84 U.S. population, 0.067; the expected lifetime of males is 69.7 yr.

Source: Adapted from Committee on the Biological Effects of Ionizing Radiations, Board on Radiation Effects Research, Commission on Life Sciences, National Research Council, 1988. Health Risks of Radon and Other Internally Deposited Alpha-Emitters. BEIR IV. National Academy Press, Washington, D.C.

Radon-Lung Cancer NUSAP[3]

Numerical Information: years of life lost/cancer risk

Units

Measurement Units: per WLM/yr for period of work history

Statistical Unit: mean (meta analysis)

Spread

Confidence Level: 95%

corresponding to ± 2 standard errors

Upper Bound: x 1.7
Lower Bound: ÷ 1.7

A 67% confidence level corresponds to the commonly used method of expressing uncertainty ± 1 standard error. The uncertainty at a 95% level of confidence, corresponding to ± 2 standard errors, would be represented by multiplication and division by 1.7.

Assessment

Informative Value Based on Spread: LOW

The analysis used provides improvements to previous analysis, but not radically so. It takes an epidemiologically-based risk approach rather than dosimetric.

Informative Value Based on Application: MEDIUM

Generalizability to Other Applications: HIGH

Robustness of Value over Time: MEDIUM

Analysis depends on population-based data (1980-84), and over a period of several decades this will change.

Pedigree (credibility of the entry's origin)

Theoretical Basis: GOOD

Mostly based on the preferred data source, epidemiological studies.

Data Inputs: EXCELLENT

Estimation Methods: EXCELLENT

Estimation Metric: GOOD

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[3]Refer to Part VI of this report for a description of the NUSAP method for describing the quality of information and data.

REFERENCES ON HEALTH EFFECTS OF RADIATION

NRC (National Research Council) (1988). Committee on the Biological Effects of Ionizing Radiations, Board on Radiation Effects Research, Commission on Life Sciences, National Research Council, *Health Risks of Radon and Other Internally Deposited Alpha-Emitters*. BEIR IV. National Academy Press, Washington, D.C.

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