

## RADON DAUGHTER EXPOSURE IN MINES, SMOKING AND LUNG CANCER

C. EDLING

*Department of Occupational Medicine, Linköping University, Linköping,  
Sweden*

This paper summarizes some recent data on lung cancer and radon daughter exposure. In mines, exposure to radon and its daughters is associated with a substantial risk of lung cancer, but there seems to be a complex relationship between radon and radon daughter exposure and smoking. Epidemiological studies as well as animal experiments indicate that radiation might be important for the initiation of lung cancer, resulting in a substantial lung cancer risk even for non-smoking miners and that smoking is likely to act mainly as a promoter.

Observations of excess deaths from »pulmonary consumption« among miners date back as far as the 16th century but it was not until 1879 that the neoplastic nature of this disease among the miners in Schneeberg in Germany was reported (1, 2, 3). Later on similar findings were also reported from Joachimsthal in Czechoslovakia (4). The etiology was unclear, however, but in 1921 the presence of radioactivity in the mines attracted interest as a possible causal factor and a few years later the attention was directly focused on the occurrence of radium emanation or radon in the mine atmosphere (5).

Radon, which is a radioactive noble gas, is created by the decay of radium (which in turn derives from uranium and is present in the ore). When radon decays in the air its short-lived radioactive daughters, isotopes of polonium, bismuth, and lead, tend to attach themselves to the nearest solid object. In air, this is usually a dust particle; when the miners inhale this air, with both attached and unattached radon daughters, radiation is most intense at places where dust is deposited. Although the radon daughters give off alpha, beta and gamma radiation, it is the alpha radiation that delivers the significant radiation dose to the tracheal and bronchial epithelium. The bronchial epithelium and particularly the basal stem cells are considered to be the tissue predominantly at risk after inhalation of radon daughters (6).

### LUNG CANCER AND RADON DAUGHTER EXPOSURE

For several decades the high lung cancer mortality among the miners in Joachimsthal and Schneeberg was thought of as a rare example of radiation induced occupational lung cancer (7). Today, however, several groups of miners have been shown to have a high incidence of lung cancer, e. g. African gold miners (8), US metal miners (9), French iron ore miners (10), Canadian fluorspar miners (11), US uranium miners (12), British haematite miners (13), Swedish zinc and lead miners (14), Swedish iron ore miners (15), Swedish sulphide ore miners (16), British tin miners (17) and US phosphate miners (18). Some of these populations have had apparent exposure to radon and radon daughters in relatively high concentrations, whereas the situation is less clear for others. Underground mining *per se*, however, does not necessarily involve a significant excess risk of lung cancer. Coal miners have no clearly increased lung cancer risk (19), and levels of radon in coal mines have been found to be low (20). Similar findings are reported for potash miners (21).

Exposure to radon and radon daughters in mines is associated with a substantial risk of lung cancer (Table 1), but other etiological suggestions have also gained some support.

Table 1

*Exposure to underground iron ore mining among patients with lung cancer (LC) and referents (R) as obtained from the death records in the parish of Grängesberg 1957-1977 (from ref. 22)*

Age groups	Patients with lung cancer or referents	Exposed	Non-exposed
Total	LC	42	5
	R	331	566
Crude rate ratio, CRR		14.4	(1.0)
Mantel-Haenszel rate ratio			
Point estimate		16.6	(1.0)
95% confidence interval		7.7-35.3	

$$EF = CF_E \times (CRR - 1) / CRR = 42/47 \times (14.4 - 1) / 14.4 = 0.83$$

EF = etiological fraction, CF = case fraction, i. e. exposed cases out of all cases

Thus, hereditary factors, dust as causing pneumoconiosis and the occurrence of arsenic have been considered to be alternative or additional explanations (23). Later on also exposure to asbestos and diesel exhausts has been added to the list of alternative explanations

and quite recently quartz exposure has been discussed as a possible etiologic factor (24). However, the exposure to these factors varies between all the mining populations studied throughout the world, whereas radon daughter exposure is a characteristic in common. It seems therefore reasonable to conclude that these other factors in the mine atmosphere are likely to be less important in lung cancer induction.

### INTERACTION WITH SMOKING

In the early studies of US uranium miners (12,25), almost every miner with lung cancer was a smoker and as a consequence smoking was thought of as the major contributor to the lung cancer risk among miners. Later observations seem to indicate, however, that there is a rather considerable lung cancer risk also for non-smoking miners (26). *Archer and co-workers* (27) found that the induction-latency time (taken as the time from first exposure to the identification of the disease outcome) for lung cancer in the uranium miners was shorter among heavy cigarette smokers than for light smokers, ex-smokers and non-smokers. A study of Swedish zinc lead miners (28) showed that non-smoking miners were even more apt to develop lung cancer than smoking miners, although later in life. The rate ratio, smokers to non-smokers, was 0.5 with an approximative 95% confidence interval of 0.08—2.9. Similarly, in a Swedish sulphide ore mine (16) the rate ratio was 0.4 with an approximative 95% confidence interval of 0.1—2.1. In a cohort study of Swedish iron ore miners in Malmberget (29) the relative risk, after correction for different smoking habits, was 2.8 for non-smokers and 3.8 for smokers. It has also been reported that among Navajo uranium miners with lung cancer, 14 out of 16 individuals were non-smokers (30).

Table 2  
*Smoking habits among 44 matched pairs of iron ore underground miners\* (from ref. 22)*

Patients with lung cancer	Referents	
	Smokers	Non-smokers
Smokers	28	10
Non-smokers	5	1
Risk ratio		2.0
95% confidence interval		0.7—5.7

\* With a condition of 10 years or more underground work and 15 years or more induction-latency time, 37 pairs remain, the discordant pairs being the same

The results of a recent study (22) confirm the view that even non-smoking miners are at about the same risk as smokers of developing lung cancer (Table 2). In another study of iron ore miners in northern Sweden the risk ratio, smokers to non-smokers, was 2.7 (31) and the 95% approximative confidence interval 0.4—18.5.

From the reports that the induction-latency time for lung cancer is significantly shorter for smoking than for non-smoking miners, one might assume that a major role of tobacco smoke could be that of a promoter, whereas radiation acts as the major cancer initiating agent. Some experimental work also supports this view. Thus, in hamsters, intratracheal instillation of the alpha particle emitting polonium ( $^{210}\text{Po}$ ) yielded only one lung cancer in 31 animals, but when this exposure was followed by 14 weekly instillations of saline, lung tumours occurred in 14 animals out of 51 (32). These results indicate perhaps that chronic irritation of almost any kind, smoking included, may potentiate lung carcinogenesis induced by alpha radiation. It has also been reported that if rats were exposed to smoke before inhaling radon no potentiating effect was observed, whereas exposure to smoke after inhalation of radon promoted tumour development, suggesting a direct promoting effect of smoking (33).

The suggestion that tobacco smoke merely acts as a promoting agent also gains support from the experience that the risk of lung cancer in ex-smokers, 10—15 years after cessation of smoking is only slightly greater than that for non-smokers (34). A promoting effect by tobacco smoke would also explain why, in the early studies in US uranium miners, almost every miner with lung cancer was a smoker, whereas non-smokers with this disease came to appear later. The observation of an effect of a promoter, say tobacco smoke, in a population, during a very short period of time, may easily lead to a premature conclusion that there is no hazard present in that population where exposure takes place only to a carcinogen with less strong promoting properties and the effect therefore occurs later in time.

The relations between lung cancer, radon daughter exposure and smoking might be even more complicated. *Altshuler and co-workers* (6) suggested that an increased thickness of the mucous sheath could decrease the effective radiation dose to the basal cells. Since it is known that smoking miners might have a higher prevalence of bronchitis (35, 36), presumably resulting in an increased mucous layer covering the epithelium, there is a possibility that this increase in depth might put the basal cells out of reach of the superficially penetrating alpha radiation. This mechanism has been proposed as a possible explanation of the findings in the zinc lead miners (28, 37). Also, an experiment on dogs has shown that smoking dogs developed less lung cancer than non-smoking dogs, when exposed to radon

daughters and uranium ore dust (38). Out of 19 dogs in each group, there were two cancers among the smokers against 9 among the non-smokers.

### QUANTITATIVE ASPECTS

Various mining populations have been compared in several reviews in the past in order to quantify the lung cancer risk, and to assess the dose-response relationship between radon daughter exposure and the risk of lung cancer. Traditionally these estimations have been based on the number of excess lung cancers per person years at observation and working level month (WLM). A working level (WL) is defined as any combination of short-lived radon daughters per litre of air that will result in the emission of  $1.3 \times 10^5$  MeV of alpha energy in their decay through RaC', and the exposure to a concentration of 1 WL for the working time during one month, taken as 170 hours, is equivalent to one working level month (WLM). One of the most recent reviews is BEIR III (39), which includes Czechoslovakian, Canadian and US uranium miners, Newfoundland fluorspar miners and Swedish metal miners. Based on the combined estimates for these miners, and the assumption of a linear relationship between exposure and outcome, BEIR III gives estimates of age-specific lung cancer excess due to radon daughter exposure in a number of cases per  $10^6$  person years and WLM. To contribute further to the quantitative information about the lung cancer risk due to radon and daughters some calculations were undertaken on the iron ore miners in Grängesberg (40). The quantitative estimates obtained from the Grängesberg miners fit in rather well with the estimates given in the BEIR III report (Table 3).

Table 3  
*Age specific estimates of excess risk of lung cancer due to radon (from ref. 40)*

Age of death from cancer	Excess risk, patients with lung cancer per $10^6$ person years, and working level month		
	BEIR III	Grängesberg	Grängesberg 10a exp time 15a induction- latency time
50—65	20	26	22
> 65	50	54	45

The effect of smoking on the risk estimates has not yet been fully evaluated in publications since the estimates are derived from mixed populations of smokers and non-smokers. If the smoking and radiation

risks are additive the excess estimate in Table 3 would apply to both smokers and non-smokers. Judging from some of the presumably most »mature« mining populations that have been specifically studied in this respect (16, 22, 28, 29) an additive interrelationship seems the more likely.

Since smoking is a strong risk factor for lung cancer, and there seems to be a complex relationship between smoking and radon daughter exposure, it might be better to calculate the risk in non-smoking populations only. Such calculations have been performed, based on data given in the studies of zinc lead miners (28) and iron ore miners (22), and are presented in Table 4.

Table 4

*Lung cancer per WLM and 10<sup>6</sup> person years among male non-smokers above 50 years of age. For the underlying assumptions and calculations (see ref. 40 and 41)*

Source population	WLM/lifetime	Lung cancers per WLM and per 10 <sup>6</sup> person years
Zinc lead miners	410.6	35.0
Iron ore miners	161.7	29.7

From these figures it might be estimated that about 29–35 cases per 10<sup>6</sup> person years and per working level month (WLM) for non-smoking males aged 50 and over could result from radon daughter exposure. This would also be the upper limit for risk estimates in non-smokers when discussing exposure to radon and its daughters as a risk factor for lung cancer in the general population. It might also be mentioned that there is a reasonable agreement between various risk estimates obtainable from miners and from the general population (42).

#### CONCLUSIONS

Various studies have shown that exposure to radon and radon daughters causes lung cancer among miners also in the absence of smoking, but smoking could shorten the induction-latency time for lung cancer. There seems to be a complex relationship between radon and radon daughter exposure and smoking, since smoking also causes bronchitis, hindering the exposure of the epithelium to the very short ranging alpha radiation, resulting in a more or less additive relation between radon daughter exposure and smoking. It is suggested that smoking is predominantly acting as a promoter, whereas alpha ra-

diation is mainly responsible for cancer induction. An estimate of about 29—35 cases of cancer per  $10^6$  person years and per working level month seems to apply on a lifetime basis to non-smoking miners aged above 50.

#### References

1. Härting, F. H., Hesse, W.: Der Lungenkrebs, die Bergkrankheit in den Schneeberger Gruben. *Vjschr. Ned. Gerich. K.*, 30 (1879) 296—307.
2. Härting, F. H., Hesse, W.: Der Lungenkrebs, die Bergkrankheit in den Schneeberger Gruben. *Vjschr. Ned. Gerich. K.*, 31 (1879) 102—132.
3. Härting, F. H., Hesse, W.: Der Lungenkrebs, die Bergkrankheit in den Schneeberger Gruben. *Vjschr. Ned. Gerich. K.*, 31 (1879) 313—337.
4. Arnstein, A.: Über den sogenannten »Schneeberger Lungenkrebs«. *Verh. Dtsch. Ges. Pathol.*, 16 (1913) 332—342.
5. Ludwig, P., Lorensen, E.: Untersuchung der grubenluft in der Schneeberger gruben auf den gehalt an radiumemanation. *Strahlentherapie*, 17 (1924) 428—435.
6. Altshuler, B., Nelson, N., Kuschner, M.: Estimation of lung tissue dose from the inhalation of radon and daughters. *Health Phys.*, 10 (1964) 1137—1161.
7. Doll, R.: Occupational lung cancer: A review. *Br. J. Ind. Med.*, 16 (1959) 181—190.
8. Oshburn, H. S.: Cancer of the lung in Gwanda. *Cent. Afr. J. Med.*, 3 (1957) 215—223.
9. Wagoner, J. K., Miller, R. W., Lundin Jr., F. E., Fraumeni, J. F., Haij, N. E.: Unusual mortality among a group of underground metal miners. *New Engl. J. Med.*, 269 (1963) 281—289.
10. Roussel, J., Pernot, C., Schoumacher, P., Pernot, M., Kessler, Y.: Considération statistique sur le cancer bronchique des mineurs de fer du bassin de Lorraine. *J. Radiol. Electrol. Med. Nucl.*, 45 (1964) 541—546.
11. de Villier, A. J., Windish, J. P.: Lung cancer in a fluorspar mining community. I. Radiation, dust and mortality experience. *Br. J. Ind. Med.*, 21 (1964) 94—109.
12. Wagoner, J. K., Archer, V. E., Carroll, B. E., Holaday, D. A., Lawrence, P. A.: Cancer Mortality Patterns Among U. S. Uranium Miners and Millers, 1950 through 1962. *J. Natl. Cancer Inst.*, 32 (1964) 787—801.
13. Boyd, J. T., Doll, R., Faulds, J. S., Leiper, J.: Cancer of the lung in iron ore (haematite) miners. *Br. J. Ind. Med.*, 27 (1970) 97—105.
14. Axelsson, O., Josefson, H., Rehn, M., Sundell, L.: Svensk pilotstudie över lungcancer nečitko
15. Jörgensen, H. S.: A study of mortality from lung cancer among miners in Kiruna 1950—1970. *Work Environ. Health*, 10 (1973) 126—133.
16. Dahlgren, E.: Lungcancer, hjärtkärlsjukdom och rökning hos en grupp gruvarbetare [Lung cancer, Cardiovascular Disease and Smoking in a Group of Mineworkers] *Lakartidningen*, 76 (1979) 4811—4814.
17. Fox, A. J., Goldblatt, P., Kinlen, L. J.: A study of the mortality of Cornish tin miners. *Br. J. Ind. Med.*, 38 (1981) 378—380.
18. Fleischer, R. L.: A Possible Association between Lung Cancer and Phosphate Mining and Processing. *Health Phys.*, 41 (1981) 171—175.

19. *Rockette, H. E.*: Mortality patterns of coal miners. In: Health implications of new energy technologies. Eds. W. N. Rom, V. E. Archer, Ann Arbor Science Publishers Inc., Ann Arbor, MI, 1980, pp. 269—281.
20. *Duggan, M. J., Soilleux, P. J., Strong, J. C., Howell, D. M.*: The exposure of United Kingdom miners to radon. *Br. J. Ind. Med.*, 27 (1970) 106—109.
21. *Waxweiler, R. J., Wagoner, J. K., Archer, V. E.*: Mortality of potash workers. *J. Occup. Med.*, 15 (1973) 486—489.
22. *Edling, C.*: Lung cancer and smoking in a group of iron ore miners. *Am. J. Med.*, 3 (1982) 191—199.
23. *Lorenz, E.*: Radioactivity and lung cancer; a critical review of lung cancer in the miners of Schneeberg and Joachimsthal. *J. Natl. Cancer Inst.*, 5 (1944) 1—15.
24. *Goldsmith, D. F., Guidotti, T. L., Johnston, D. R.*: Does Occupational Exposure to Silica Cause Lung Cancer? *Am. J. Ind. Med.*, 3 (1982) 423—440.
25. *Wagoner, J. K., Archer, V. E., Lundin Jr., F. E., Holaday, D. A., Lloyd, J. W.*: Radiation as the cause of lung cancer among uranium miners. *New Engl. J. Med.*, 273 (1965) 181—188.
26. *Lundin Jr., F. E., Wagoner, J. K., Archer, V. E.*: Radon daughter exposure and respiratory cancer quantitative and temporal aspects. NIOSH — NIEHS Joint Monograph No. 1, 1971. US Department of Health, Education and Welfare, Public Health Service.
27. *Archer, V. E., Wagoner, J. K., Lundin Jr., F. E.*: Uranium Mining and Cigarette Smoking Effects on Man. *J. Occup. Med.*, 15 (1973) 204—211.
28. *Axelsson, O., Sundell, L.*: Mining, lung cancer and smoking. *Scand. J. Work Environ Health*, 4 (1978) 46—52.
29. *Radford, E. P.*: Radon Daughters in the Induction of Lung Cancer in Underground Miners. In: Banbury Report 9: Quantification of Occupational Cancer. Eds. R. Peto, M. Schneiderman, Cold Spring Harbor, NY: Cold Spring Harbor Laboratory, 1981, pp. 151—163.
30. *Gottlieb, L. S., Husén, L. A.*: Lung Cancer among Navajo Uranium Miners. *Chest*, 81 (1982) 449—452.
31. *Damber, L., Larsson, L.-G.*: Combined effects of mining and smoking, in the causation of lung carcinoma. A case-control study in northern Sweden. *Acta Radiol. Oncology*, 21 (1982) 305—313.
32. *Little, J. B., Kennedy, A. R.*: Evaluation of Alpha Radiation-Induced Respiratory Carcinogenesis in Syrian Hamsters: Total Dose and Dose-Rate. *Prog. Exp. Tumor Res.*, 24 (1979) 356—369.
33. *Chameaud, J., Perraud, R., Chrétien, J., Masse, R., Lafuma, J.*: Lung Carcinogenesis during in Vivo Cigarette Smoking and Radon Daughter Exposure in Rats. *Recent Results Cancer Res.*, 82 (1982) 11—20.
34. *Surgeon General*. Smoking and Health. A report of the Surgeon General, US Dept of Health, Education and Welfare, Washington, Public Health Service, 1979.
35. *Jørgensen, H., Swensson, A.*: Undersökning av arbetare i gruva med dieseldrift, särskilt med hänsyn till lungfunktion, luftvägssymptom och rökvanor. (AI-rapport no. 16, 18 pp.) Arbetsarkyddverket, Stockholm, 1970 (English summary).
36. *Stuis-Cremer, G. K., Walters, L. G., Sichel, H. S.*: Chronic Bronchitis in Miners and Non-miners: An Epidemiological Survey of a Community in the Goldmining Area in the Transvaal. *Br. J. Ind. Med.*, 24 (1967) 1—12.
37. *Axelsson, O., Sundell, L.*: Mining, lung cancer and smoking. *Scand. J. Work Environ. Health*, 6 (1980) 227—231.



38. Cross, F. T., Palmer, R. F., Filipy, R. E., Dagle, G. E., Stuart, B. O.: Carcinogenic effects of radon daughters, uranium ore dust and cigarette smoke in beagle dogs. *Health Phys.*, 42 (1982) 33—52.
39. BEIR III. Committee on the Biological Effects of Ionizing Radiations: The Effects on Populations of Exposure to Low Levels of Ionizing Radiation. National Academy of Sciences, Washington D. D., 1980.
40. Edling, C., Axelson, O.: Quantitative aspects of radon daughter exposure and lung cancer in underground miners. *Br. J. Ind. Med.*, 40 (1983) 182—187.
41. Axelson, O., Edling, C.: Health hazards from radon daughters in dwellings in Sweden. In: Health implications of new energy technologies. Eds. W. N. Rom, V. E. Archer, Ann Arbor Science Publishers Inc., Ann Arbor, MI, 1980, pp. 79—87.
42. Edling, C., Comba, P., Axelson, O., Flodin, U.: Effects of low-dose radiation — A correlation study. *Scand. J. Work Environ. Health*, 8 Suppl. (1982) 59—64.

#### Sažetak

#### EKSPOZICIJA PRODUKTIMA RADONA U RUDNICIMA, PUŠENJE I RAK PLUĆA

Prikazani su najnoviji podaci o povezanosti ekspozicije radioaktivnim produktima radona i pojave raka pluća u rudara. Plemeniti plin radon nastaje raspadom radija, koji pak potječe iz raspada urana. Produkti radona su kratkoživi radioaktivni izotopi koji se vežu uz čvrste lebdeće čestice što se udišu i deponiraju u plućima a emitiraju alfa, beta i gama-zrake. Ovom su zračenju posebno intenzivno izvrgnute stanice bronhalnog epitela. Osim opasnosti koja je odavno poznata za rudnike urana, danas se povećana učestalost raka pluća u radnika iz drugih rudnika (zlata, željeza, cinka, olova, itd.) povezuje s prisutnošću radonovih radioaktivnih izotopa. U posebnim epidemiološkim ispitivanjima utvrđeno je da je pušenje favorizirajući činilac i da je među rudarima pušačima rak pluća još značajno češći. Međutim, rudari nepušači iz pojedinih rudnika izvrgnuti su podjednakom riziku od raka pluća kao i pušači drugih profesija. Ima indicija da pušenje djeluje kao promotor nastanka raka pluća jer su rudari bivši pušači izvrgnuti tek neznatno većem riziku u usporedbi s nepušačima. S druge pak strane ima pokazatelja da je odnos između ekspozicije radonovim produktima te pušenja s jedne, i nastanka raka pluća s druge strane, mnogo kompleksniji, jer pušenje izaziva bronhitične promjene pri čemu nastaje zadebljanje sluznice, a to umanjuje učinak alfa-zračenja radonovih radionuklida. Na temelju do sada poznatih podataka procjenjuje se da rak pluća uzrokovan radioaktivnim produktima radona nastaje u 29—35 nepušača starijih od 50 godina, na svakih milijun nepušača — u odnosu na puni radni vijek.

*Odjel medicine rada, Sveučilište Linköping,  
Linköping, Švedska*