

Mortality among pyrite miners with low-level exposure to radon daughters

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BATTISTA G, BELLI S, CARBONCINI F, COMBA P, LEVANTE G, SARTORELLI P, STRAMBI F, VALENTINI F, AXELSSON O. Mortality among pyrite miners with low-level exposure to radon daughters. *Scand J Work Environ Health* 14 (1988) 280—285. A cohort mortality study was conducted with regard to a pyrite mine located in central Italy. Exposure to radon ranged from 0.12 to 0.36 working levels (WL) in the work areas; most measurements were around 0.2 WL. The concentration of free silica in the dust was less than 2 %. The cohort was determined from company files and included 1 899 subjects. Mortality was studied for the years 1965—1983. The loss to follow-up was less than 2 %. The standardized mortality ratio for all causes and all neoplasms was 97 and 107, respectively. That for lung cancer and for nonmalignant respiratory diseases was 131 (95 % confidence interval 97—175) and 173 (95 % confidence interval 135—231), respectively. It was estimated that the extra cases of lung cancer attributable to radon daughters numbered 13 per 10⁶ person-years and working level month in the whole cohort and 21.3 per 10⁶ person-years in the subcohort with 10—25 years of exposure.

Key terms: cohort study, iron ore mining, lung cancer.

The occurrence of respiratory cancer among miners has been studied in several European countries, the United States, the Soviet Union, Canada, and South Africa, both in uranium and other mines. The inhalation of radon daughters has been considered the main risk factor for respiratory cancer, even if the authors have not always evaluated other mineral carcinogens, such as asbestos, nickel or arsenic, in their studies.

This report considers underground iron ore miners with a low level of exposure to radon daughters, and the intention is to provide further data for the estimation of risk in the low-dose range. Iron ore miners have been subject to several investigations already, but the importance of radon daughter exposure in these mines has not been immediately clear. Faulds & Stewart (9) noted a high proportion of deaths from lung cancer among hematite miners in West Cumberland; Boyd et al (4) extended the study and confirmed the findings. A high proportion of iron ore miners among lung cancer patients in Lorraine was reported by Roussel et al (20), and subsequently confirmed by Antoine et al (1) and Pham et al (18). An excess of lung cancer has been reported among iron miners from Czechoslovakia (11). An excess of lung cancer among iron ore miners in northern Sweden has been detected both in case-referent studies (7, 15) and by a cohort approach (13).

A series of recent reports has shed new light on the issue of lung cancer among iron ore miners. It indicates the importance of radon daughter exposure in this context, since lung cancer seems to be mainly related to the occurrence of radon daughters in the mine atmosphere. Hence, for several iron ore mines, there are now estimates available with regard to the excess risk of lung cancer in relation to radon daughter exposure. For example, Radford & St Clair Renard (19) found an excess of 19 lung cancer cases per working level month and 10⁶ person-years in a miner population without any age restrictions, and Edling & Axelsson (8) found 34.8 cases per working level month and 10⁶ person-years as an average for persons 50 or more years of age [a working level (WL) is defined as any combination of short-lived radon daughters in 1 l of air that results in an ultimate emission of $1.3 \cdot 10^5$ MeV of potential alpha energy; a working level month (WLM) is equal to an exposure time of 170 h]. On the other hand, a study of hematite miners in Minnesota did not provide evidence of any increased risk of lung cancer in the absence of significant radon exposure (16). Nor did a cohort study conducted in Norway (17) among magnetite miners exposed to a concentration of 0.10—0.15 WL detect any increased risk of lung cancer, but the study was limited in size, with a relatively low power of detecting small risks. It can thus be stated that the recent evidence shows a consistent excess of lung cancer among underground iron miners in relation to radon daughter exposure. Correspondingly, it might also be noted that iron oxide has not been found to be carcinogenic in humans in another occupational situation (3). Experimental studies reviewed by the International Agency for Research on

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Cancer (12) suggest that ferric oxide lacks any carcinogenic activity, while there is inadequate evidence of carcinogenicity for hematite.

The miners studied in the present investigation have extracted pyrite (FeS_2) in a mine located in the province of Grosseto (Tuscany, Italy). The radon daughter levels were estimated to have been about 0.2 WL for a long period of time, and thereby this study contributes additional information about the risk at low exposure levels.

Subjects and methods

The mine

The mine in which the study took place was active from 1936 to 1983; the average work force was about 1 200 miners, decreasing to about 400 in more recent years. The work took place at four different levels, the deepest one at about 350 m. Forced ventilation provided an airflow rate of 60–80 m^3/s .

According to measurements performed by the company, the excavated material contained iron (37–44 %), sulfur (38–48 %), and free silica (1–2 %). The ore also contained microquantities of magnesium oxide (0.2–1 %), aluminum oxide (0.1–0.4 %), copper (0.003 %), zinc and lead (0.010 %), arsenic (0.018–0.80 %), cobalt (0.0363 %), and nickel (0.0029 %) (5). The uranium in the surrounding rocks ranged from 0.0006 % in the schists to 0.0008 % in the quartz seams to 0.0013 % in the anhydrite; these values are somewhat higher than those usually detected in other Italian nonuranium mines (6).

About 2 750 t of mineral per day was delivered to plants which used it in the production of sulfuric acid and “pellets” for the steel industry. Wet drilling was introduced around 1958; the use of diesel engines started around 1974. Smoking was prohibited in the mine in 1952. Environmental monitoring of mineral dust was performed from the early 1970s on.

Table 1 summarizes the results of the airborne dust sampling from 1970 to 1976 (optical microscopy

method) and from 1977 to 1983 (X-ray diffraction). It is remarkable that the highest values were recorded during ore removing in the years following the entry of diesel engines (1975–1976). The lower variability of the data collected after 1977 is presumably due both to the preventive measures and to the new method of analysis initiated. Levels of airborne dust sometimes exceeded the standard of the American Conference of Governmental Industrial Hygienists (ACGIH) in the earlier period, but not in recent years (22). No information on exposure associated with dry drilling was available.

The concentrations of carbon oxide, nitrogen oxide, and sulfur oxide gases in the environment were found to comply with the ACGIH standards. The nitroglycerin and nitroglycerol levels, after explosions, showed peak values of up to 0.20 ppm [mean 0.07 (SD 0.09) ppm, ACGIH time-weighted average 0.05 ppm].

Measurements of exposure to potential alpha energy of short-lived ^{222}Rn daughters were carried out in 20 workplaces in 1979 by the Commission of the Institute of Nuclear Protection and Safety of France using individual active dosimeters (6). The results are summarized in table 2.

The radon gas concentration was evaluated in 1981–1984 in various areas of the mine by a team of the National Agency for Energy (ENEA) (23). Individual passive dosimeters were used, and the results are shown in table 3.

The equilibrium factor ranged from 0.50 to 0.80 at the dead end of the drift. The data obtained from passive and active dosimeters agreed well with measurements performed in areas without forced ventilation (23). The authors stated that the measurements carried out for the upcast air may be considered representative of the average radon concentration in several locations.

In conclusion, radon exposure ranged from 0.08 to 0.40 WL; most measurements were about 0.2 WL (unpublished data from the Ministry of Industry, 1985), and this level has been considered to be representative of past exposure also.

Table 1. Airborne dust in the underground environment. (This table has been adapted from reference 22.)

Type of job	1970–1976 ^a		1977–1983 ^b	
	Mean	Range	Mean	Range
Drilling				
Inhalable dust	802	605–1 270	1.22	0.53–1.55
Quartz content (%)	3.16	0.89–4.27	1.48	0.78–3.81
Ore removing				
Inhalable dust	2 658	615–8 603	1.32	0.99–2.02
Quartz content (%)	3.13	0.84–4.30	1.88	1.20–2.54
Other				
Inhalable dust	446	280–1 051	0.33	0.09–0.47
Quartz content (%)	2.60	0.35–3.83	1.67	1.40–2.03

^a Optic microscopy, particles per cubic centimeter.

^b X-ray diffraction, milligrams per cubic meter (personal sampling in 1983).

Table 2. Monthly exposure to potential alpha energy of short-lived ^{222}Rn daughters in different types of work (1 WLM = $3.6 \cdot 10^{-3} \text{ J} \cdot \text{m}^{-3} \cdot \text{h}$). (This table has been adapted from reference 6.)

Type of job	Mean ($\text{mJ} \cdot \text{m}^{-3} \cdot \text{h}$)	Range ($\text{mJ} \cdot \text{m}^{-3} \cdot \text{h}$)
Drilling	0.40	0.29—0.62
Ore removing	0.56	0.45—0.72
Other	0.35	0.28—0.47
Total	0.42	..

Table 3. ^{222}Rn gas concentration in the mine environment (1 WL = 3.7 KBq/m^3 at equilibrium). (This table has been adapted from reference 23.)

Location	Radon concentration (KBq/m^3)	
	1981	1984
Shaft	0.41	0.87
Drift	0.94	1.26
Stope	0.81	0.58
Upcast air	1.41	0.58

Table 4. Distribution of the person-years at risk by calendar time and age.

Calendar time	Person-years
1965—1969	7 490
1970—1974	7 988
1975—1979	8 105
1980—1983	5 994
Total	29 577
Age group (years)	
≤34	2 430
35—44	5 867
45—54	8 631
55—64	7 719
≥65	4 930
Total	29 577

The cohort

The cohort was determined from the company files and included all the subjects active on 1 January 1950 and still alive on 1 January 1965, along with those subsequently employed until 1 January 1983. The years prior to 1950 were not included because of the low reliability of data of wartime years. The collection of mortality figures was started in 1965 due to considerations of the quality of the certification of causes of death in the area of interest.

Admission to the cohort was restricted to underground workers. Altogether 1 899 male subjects fulfilled the admissibility criteria; their average duration of employment was 13 years. Their mortality experience was studied from 1 January 1965 through 31 December 1983.

The information on the vital status and the causes of death of the subjects was obtained from the files of the municipalities where the miners lived and/or died. The loss to follow-up was less than 2 %. Lost subjects were assumed to be alive at the end of the follow-up. The causes of death were independently coded by three physicians, according to the eighth revision of the International Classification of Diseases and Causes of Death (ICD), since the death certificates available in the municipalities do not report the ICD codes (which are available at the Central Institute of Statistics, where data are processed anonymously).

The analysis of the data was performed with the life-table analysis system of the National Institute for Occupational Safety and Health in the United States. The expected numbers were based on Italian mortality rates, specific for cause, sex, age, and calendar period. A description of the cohort in terms of the distribution of person-years by duration of exposure and calendar time is shown in table 4.

Results

The mortality experience of the cohort is shown in table 5. Altogether 463 deaths occurred versus 474.6 expected. The observed deficit in mortality from circulatory diseases (standard mortality ratio 74) is likely to depend on selection to work and other circumstances and is usually referred to as the healthy worker effect. This phenomenon is generally seen in this type of study. No excess of ischemic heart disease or cerebrovascular disease was detected.

The statistically significant excess of nonmalignant respiratory diseases has been presented in greater detail in table 6. Virtually all the extra cases, defined as the difference between the observed and expected figures, occurred after 10 years of latency and 10 years of exposure. Out of 67 cases of nonmalignant respiratory disease, 43 were recorded as silicosis and three as massive silicosis, but no death was referred to as silicotuberculosis.

Among the subjects whose cause of death was silicosis 14 % had worked up to 10 years, 63 % had worked for 11—20 years, and 23 % had worked for more than 20 years. Sixty-three percent of the deaths occurred in the first 15 years of the study (1965—1979), while 37 % took place in the years 1980—1983. Thus the mortality due to silicosis seems to be still increasing. The prevalence of pneumoconiosis among the active miners, in 1983, was 4 %, based on 12 subjects with an average duration of employment of 25 years (22). The mortality figures may overestimate the occurrence of silicosis due to the fact that compensation is awarded to widows and heirs if the death is attributable to silicosis, even in the absence of autopsy.

For most of the sites, cancer mortality in the cohort was in agreement with the national figures (table 5). Excesses of intestinal cancer and lymphohematopoietic

Table 5. Mortality experience of the cohort (1965–1983). (O = number of observed deaths, E = number of expected deaths, SMR = standardized mortality ratio, 95 % CI = 95 % confidence interval)

Cause ^a	O	E	SMR	95 % CI
All causes	463	474.6	97	89–107
All neoplasms	134	125.0	107	91–127
Malignancies of the pharynx	5	4.9	101	33–237
Malignancies of the esophagus	3	3.5	86	18–253
Malignancies of the stomach	19	18.9	100	61–157
Malignancies of the intestine	14	7.6	183	100–307
Malignancies of the larynx	4	5.1	77	21–199
Malignancies of the lung	47	35.6	131	97–175
Malignancies of the prostate	5	6.4	78	25–183
Malignancies of the bladder	3	5.3	56	12–165
Malignancies of the lymphohematopoietic tissue	10	7.7	130	63–240
Diseases of the circulatory system	150	201.3	74	63–87
Diseases of the respiratory system	67	38.5	173	135–231
Cirrhosis of the liver	25	27.9	89	58–133
Accidents	39	23.7	164	117–225

^a The reported causes of death are not exhaustive.

malignancies were detected, but due to the smallness of the figures and the lack of a priori hypotheses, no definite conclusions can be drawn. It may be noted, however, that five cases in the latter group were lymphosarcomas and reticulosarcomas (standardized mortality ratio 320).

The excess of lung cancer (standardized mortality ratio 131) is presented in more detail in table 7. It may be noted that the extra cases usually occurred after 10 years of latency, especially among subjects with 10–25 years of exposure. Their mean age at death was 61 years.

The concentration of radon daughters in the mine has been estimated to be about 0.2 WL, leading to an accumulated exposure of about 2.2 WLM per year. On the basis of the number of cases and person-years in the different exposure categories, it is possible to obtain a risk estimate of 13.0 cases per 10⁶ person-years and working level month. Since most of the extra cases occurred in the exposure category 10–25 years, an estimate restricted to this portion of the cohort would increase to 21.3 cases per 10⁶ person-years and working level month.

Table 6. Distribution of the observed (O) and expected (E) non-malignant respiratory diseases by duration of exposure and latency.

Latency (years)	Exposure (years)							
	< 10		10–25		> 25		Total	
	O	E	O	E	O	E	O	E
< 10	1	0.9	—	—	—	—	1	0.9
10–25	6	6.1	15	5.9	—	—	21	12.0
> 25	6	5.7	32	16.0	7	3.9	45	25.6
Total	13	12.7	47	21.9	7	3.9	67	38.5

Table 7. Distribution of the observed (O) and expected (E) lung cancer deaths by duration of exposure and latency.

Latency (years)	Exposure (years)							
	< 10		10–25		> 25		Total	
	O	E	O	E	O	E	O	E
< 10	1	1.7	—	—	—	—	1	1.7
10–25	6	5.5	13	6.6	—	—	19	12.1
> 25	5	3.5	19	13.7	3	4.6	27	21.8
Total	12	10.7	32	20.3	3	4.6	47	35.6

Table 8. Cigarette smoking habits of the miners and referents. (This table has been adapted from reference 22.)

Group	Smokers		Ex-smokers		Nonsmokers		Total		Amount smoked by smokers ^a	
	N	%	N	%	N	%	N	%	Mean	SD
Underground miners (drilling and ore removing)	79	61.7	20	15.6	29	22.7	128	100	15.5	8.5
Underground service workers	104	63.8	21	12.9	38	23.3	163	100	11.1	8.1
Surface service workers	46	61.3	12	16.0	17	22.7	75	100	11.2	8.7
Referents	176	54.7	61	18.9	85	26.4	322	100	13.7	10.2

^a Product of the average daily number of packages and the corresponding number of years.

Discussion

The present study was based on the traditional cohort approach in occupational epidemiology, involving well-known limitations, especially with regard to phenomena of incomparability between a working population and the general population as providing the rates underlying the expected numbers.

It can be seen that the overall mortality (standardized mortality ratio 92) falls in a range which is relatively typical in occupational mortality studies. The deficit of circulatory deaths is consistent with preemployment selection concerning the fitness of miners with respect to underground work. In this framework the excess of respiratory diseases, both malignant and nonmalignant, appear to be work-related, especially since the extra cases occurred when an adequate latency time had elapsed since first exposure.

A second major limitation of cohort studies of this kind is represented by the absence of the control of smoking, which is somewhat disturbing with regard to lung cancer. In this particular investigation, the smoking habits of all the cohort members were not known, but two comments can be made on the basis of some recent views on this issue (24). First, a cross-sectional study carried out with respect to workers active in this mine (22) showed that the proportion of smokers was compatible with that of a random sample of the male population in this area, as shown in table 8. Secondly, several smoking-related causes of death, like larynx and bladder cancer, as well as circulatory diseases, did not occur at an increased rate in this cohort. It may be noted also that cigarette smoking and alcohol consumption tend to be associated, and such causes of death as pharyngeal and esophageal cancer and cirrhosis of the liver did not occur in excess in the cohort.

The current interest in epidemiologic studies on lung cancer incidence among miners is mainly focused on the dose-response relationship to radon daughter exposure. Research conducted in the uranium mines in the United States (2, 21), Canada (10), and Czechoslovakia (14) have considered cumulative exposures ranging from 1 to 1 000 WLM, or even 2 000 WLM.

Radford & St Clair Renard (19) estimated that a figure of 18–21 extra cases was derivable from the paper by Kunz et al (14). Howe et al (10), in a recent study, provided an estimate of 21 extra cases, all estimates without any specification of the age range.

Conventional metal mines generally show cumulative exposure ranging from 1 to 100–200 WLM.

In the present study, it can be estimated that the highest cumulative exposures were not more than about 80–90 WLM, and the mean cumulative exposure was about 30 WLM. More important however is that, on the basis of these data, it does not seem necessary to assume any substantially stronger effect per dose obtained from low-level exposures than from higher levels. The risk estimates from the present study, though

based on estimates of exposure affected by some approximation, appear to be in the range of findings of the aforementioned studies from various countries. Other potential risk factors for lung cancer (silica, arsenic) were present in the mine in low concentrations, whereas diesel equipment was introduced in relatively recent times. Thus the moderate observed excess of lung cancer can, with reasonable confidence, be referred to the exposure of the cohort to radon daughters in the low exposure range.

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