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Lene H. S. Veiga · Eliana C. S. Amaral
Didier Colin · Sérgio Koifman

A retrospective mortality study of workers exposed to radon in a Brazilian underground coal mine

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Abstract Recently a high radon concentration was detected in the underground coal mine of Figueira, located in the south of Brazil. This coal mine has been operating since 1942 without taking cognizance of the high radon environment. In order to assess possible radon-related health effects on the workers, a retrospective (1979–2002) mortality study of 2,856 Brazilian coal miners was conducted, with 2,024 underground workers potentially exposed to radon daughters. Standard mortality ratio (SMR) analysis hints at lower mortality from all causes for both underground (SMR = 88, 95% CI = 78–98) and surface workers (SMR = 96, 95% CI = 80–114). A high statistically significant SMR for lung cancer mortality was observed only in the underground miners (SMR = 173, 95% CI = 102–292), with a statistically significant trend reflecting the duration of underground work. High statistically significant SMRs were observed for pneumonia as a cause of death between both surface (SMR = 304, 95% CI = 126–730) and underground miners (SMR = 253, 95% CI = 140–457). Because mortality from smoking-related cancers other than lung cancer was not found elevated in underground workers and because diesel equipments were not used in this mine, it can be concluded that the enhanced lung cancer mortality observed for underground miners is associated with exposure to radon and radon daughters, rather than other confounding risk factors.

L. H. S. Veiga (✉) · E. C. S. Amaral
Instituto de Radioproteção e Dosimetria, Av. Salvador Allende s/n, Cx. Postal 37750, Rio de Janeiro, Brazil
E-mail: lene@ird.gov.br
Tel.: +55-21-34118089
Fax: +55-21-24422699

D. Colin
International Agency for Research on Cancer, Lyon, France

S. Koifman
Escola Nacional de Saúde Pública, Fundação Oswaldo Cruz, Rio de Janeiro, Brazil

Present address: E. C. S. Amaral
International Atomic Energy Agency, Vienna, Austria

Introduction

An increased risk of lung cancer is well documented in metal and fluorspar miners who have worked underground, and this excess risk is proportional to the cumulative exposure to alpha radiation from short-lived radioactive daughters of ^{222}radon gas in mines [1–9]. Conversely, among underground workers in coal mines, in which levels of radon daughters are generally low, little excess of lung cancer has been found [2, 10–18]. This evidence may be taken to indicate that exposure to radon daughters is the principal cause of lung cancer in underground mines [19].

In Brazil, the situation of radon exposure in underground mines is still largely unknown. Only recently did the Brazilian Nuclear Energy Commission establish a regulatory position containing requirements for safety and radioprotection in non-uranium mining industries. For underground workplaces an intervention level of 1,000 Bq m^{-3} radon concentrations was established [20].

According to the National Department of Mineral Production (DNPM), there are 74 underground mines in Brazil [21]. Of these, approximately 33 are active mines, with approximately 3,200 workers in underground activities. Among these, eight are coal mines, seven are gold mines, while the others are fluoride, beryllium, feldspar, lead, iron/manganese, zinc/cadmium and tungsten mines.

In 1995, the Brazilian Nuclear Energy Commission conducted a national program in order to investigate the potential environmental and occupational radiological impacts associated with some non-uranium mining and milling industries [22, 23]. The results of this project called attention to the Figueira coal mining, an industry located in Parana State, in the south of Brazil (Fig. 1),

Fig. 1 Localization of the Brazilian coal mine in this study

which presented with high levels of radon concentration. High values of ^{210}Po in urine samples of some workers from this mine indicated the inhalation of radon progeny as a relevant source of occupational exposure [24].

The Figueira mine geological characteristics have been described elsewhere [25]. In short, the coal basin region is situated near a uranium deposit, wherein uranium mineralization is located in the sedimentary sequence between the coal seam and the calcareous horizon comprising siltite and limestone. Coal is usually found associated with sandstones, carbonaceous siltites and coal seams. In sandstones, the uranium mineralization is observed as uraninite, and around 70% of the uraninite can be found in the sandstone, and 30% in carbonaceous siltites and coal.

Veiga et al. [26] presented an evaluation of radon and radon decay products exposure in the underground environment of this coal mining industry and estimated an average annual exposure to radon progeny of 2.1 WLM,[1] with a range from 0.2 to 7.2 WLM. These measurements, however, reflect only present exposure, since the degree of radon exposure in the past is unknown. This coal mining industry has been operating since 1942 and almost 4,000 workers have since worked underground without being subjected to any regulatory requirements.

Considering that ventilation systems and mine architectures have been improving over the time, it can be assumed that radon concentrations in the past may have been higher than at present. Such a time dependence with poorest working condition in the first decades was observed in other mines [27].

It was decided to conduct a historical cohort study to investigate whether underground workers of the Figueira industry were affected by elevated lung cancer mortality and whether it could be related to radon exposure.

[1]One working level (WL) equals any combination of radon progeny in 1 l of air which results in the ultimate emission of 130,000 MeV of energy from alpha particles. It corresponds to an activity concentration of 3700 Bq m^{-3} for 222 Rn. One WLM is the exposure of 1 WL during 170 h month^{-1} or 3.5×10^{-3} Jh m^{-3}.

Materials and methods

Study subjects

The formation of the cohort and the multiple strategies for follow-up were described [28]. Briefly, all male workers employed at the Figueira coal mining industry between 1942 and 1997, for at least 1 year and for which complete occupational history was available, were eligible for the study. Women were not considered because of their small number and because they have worked only at the surface. Short-term employees (less than 1 year) were excluded from the analysis because of the difficulties in tracing them, as was also reported in others publications, and because they may represent a different population [29–31].

Of the 4,859 company personnel recorded, 1,625 were excluded (1,477 with less than 1 year of employment, 28 with missing workplace information and 130 women). Therefore, the cohort subjects under study comprise 3,224 workers, of which 2,279 (71%) were underground miners and 945 (29%) surface workers. Surface workers were those who had never worked underground, which includes both surface miners and administrative staff (less than 10% of the total surface workers).

Determination of vital status

The workers' vital status information was ascertained from the mine company records, the Regional Electoral Court, the National Social Security Institute and the Federal Revenue and Customs Secretariat. In addition, an active search was carried out at 78 death registration offices of the State of Parana, where the mine is located. The central strategy of follow-up was via the Electoral Court, by which the vital status of 53% of the members of the cohort was identified. The cohort was matched against the national voter registration list for the years 1994, 1996, 1998, 2000 and the last president election on 27 October 2002, the date of the end of follow-up. The last voting register in which a cohort member was found listed was considered as the last known vital status date.

As the regional general population death rates needed for most analyses were available only for 1979 and later, the follow-up period began on the date of hire or 1 January 1979, whichever was later. Because cohort subjects were required to have at least one year of employment, person-years were accumulated beginning 1 year after the hiring date. Therefore, the individual starting of follow-up was defined as the hiring date plus 1 year or 1 January 1979, whichever was later, and the follow-up ending was defined as one of the following dates: date of death, the last known vital status date (for those lost to follow-up), or 27 October 2002, the cutoff date for follow-up.

Causes of death were generally obtained from the Health Office of the State or the Death Registration Offices wherein the death was registered. Cause of death was ascertained for 100% of the known deceased cohort members after 1979. The underlying cause of death was coded by an expert nosologist according to the International Classification of Diseases (ICD) 9 for deaths before 1995 and ICD 10 for deaths thereafter, establishing equivalence between the different revisions.

Exposure information

Coal miners' environments include many well-known threats: dust of coal and waste rock, fumes and noxious gases, radiation (radon and radon daughters), noise and vibrations, poor light, work in a forced position together with the lack of oxygen, unfavorable microclimate (high temperature and air humidity) and stress due to the awareness of the risk of death [32]. The most frequent occupational diseases are silicosis together with complications (e.g., tuberculosis, bronchitis, emphysema and chronic respiratory system disease of unknown etiology) and skeleton pathologies, such as osteoarthritis and meniscus disorders [33–36].

Exposure to radon and radon progeny in the coal mine studied was only estimated for a recent period and the procedure is presented elsewhere [26]. Briefly, workplace and individual radon measurements were performed during three sampling campaigns in 1999, 2000 and 2003. A total of 92 individual radon measurements were carried out by using etched track dosimeters fixed to the workers' helmets during their working-period. An overall average individual radon concentration was estimated to be about 1.7 kBq m^{-3}, ranging from 0.2 to 6.1 kBq m^{-3}, considering all individual radon measurements. Based on this, an average annual exposure to radon progeny of 2.1 WLM (ranging from 0.2 to 7.2 WLM) was estimated, taking into account the conversion coefficient of 1.26×10^{-3} WLM per (Bq m^{-3}) [37].

No measurements were available prior to 1995 and the challenge was to estimate the cumulative exposure since many uncertainties could arise from using current radon measurements when making inferences on the past levels for such a long period. Radon levels may have been different in the past due to many factors, such as changes in ventilation pattern, structural alterations in the mine along the time and also the different environmental and geological conditions of all exploited excavations sites.

The cumulative radon exposure will depend on the duration of exposure, kind of job, calendar year and specific mine environment conditions. Although underground miners worked in different kinds of job during their working-life time, this information was not always recorded and most of the registers provide only information about the work place: surface or underground. The only information available that can be used as a surrogate for radon exposure was the duration of employment. Therefore, it was decided to rely on duration of employment at underground jobs as a surrogate for radon exposure.

Regular measurements of airborne dust from personal and static sampling devices became available starting in the 1980s. Respirable dust concentrations at underground workplaces averaged < 10 mg m^{-3}. As the Figueira mine is a non-methane hazard mine, electrical power was used underground instead of diesel-powered equipment. Therefore, diesel fumes do not constitute an important environmental carcinogen in this mine.

Data analysis

The principal aim of this study was to screen an increased risk of death from cancer, mainly from lung cancer, in underground miners as compared to a reference population, and to verify whether the risk increases as a function of duration of employment underground, which serves as a surrogate for exposure to radon and its daughter products.

The standardized mortality ratio (SMR) was the measure of association used to compare the workers' mortality rates with that experienced by the general male population of the State Parana, in which the mine industry is located. The SMR was computed as the ratio of observed to expected numbers of deaths multiplied by 100, using the STATA Statistic Data Analysis Software. The numbers of deaths and person-years of follow-up experience were grouped into strata defined by age (10 years intervals from 10 to 19 through 70–79, and > 80) and calendar interval (1979–1983, 1984–1987, 1988–1991, 1992–1995, 1996–1999 and 2000–2002). The expected numbers of deaths were calculated by applying the regional male mortality rates per calendar year and 10-year age range to the number of person-years corresponding to the cohort. The 95% confidence intervals (CIs) of the SMRs were calculated by assuming a Poisson distribution for the observed number of deaths and tests for homogeneity and for the trend of SMRs [38].

For certain causes of death in excess, we analyzed subgroups specified on the basis of the period of hire, years since first exposure or underground exposure duration (employment duration). Rate ratios between SMRs from exposed workers and unexposed workers (surface workers) were calculated as an indicative of the relative risk (RR). Person-years were distributed by age and calendar year into employment duration strata

(< 5 years, 5–10 years, > 10 years). Miners who worked for more than 5 years contributed their person-years to all previous categories according to the current employment duration in each year of follow-up. Workers who started as a surface worker and then became a underground worker contributed person-years to both categories.

Results

Characteristics of the cohort

Characteristic of the initial 3,224 cohort members is described elsewhere [28]. Briefly, the cohort was divided into three subcohorts based on the date of first employment, i.e., subcohort A (1942–1969), subcohort B (1970–1981) and subcohort C (1982–1997). This stratification aimed at reflecting the different environmental mining conditions in each period. There are more miners in subcohort C (hiring between 1982–1997; 43%) than in subcohorts A and B (25 and 32%, respectively). The proportion of underground workers was the same for subcohorts A and B (74%) and slightly lower for the subcohort C (66%). The mean age at first admission was around 26 years and the mean duration of employment was 6 years at underground and 5 years at surface. At the end of the follow-up period on 22 October 2002, the vital status was ascertained for 92% of the cohort members (2,950/3,224). It was established that 92 deaths occurred before 1979, 438 deaths occurred after 1979 and 2,192 subjects (68%) were alive at the end of follow-up. Another 227 subjects were alive in any period between 1979 and 2001, but lost thereafter. Vital status remains totally unknown for 275 subjects, 94% of which belong to subcohort A (1942–1969).

The 275 subjects (8.5%) lost to follow-up before 1979 and the 92 subjects who died before 1979 were not included in the SMR analysis. Subjects known to be alive in any period between 1979 and 1997 contributed person-years until the last date they were known to be alive. Subjects known to be alive at any period between 1998 and 2001 were considered alive at the end of the follow-up, since their names were traced at the death information system of the State Health Office and no records were found. Therefore, the total number of subjects included in the SMR analysis consisted of 2,856 male workers (2,024 underground workers and 832 surface workers).

Table 1 presents the characteristics of the 2,856 miners included in the study. The cohort contains a small proportion (6.5 %) of miners still working at the end of the follow-up. The total number of person-years was 48,991, with a mean follow-up duration of 17 years. At the end of the study, 77% of the miners in the cohort were still alive. The attained age was 65 years for subcohort A and only 38 years for subcohort C, indicating this as a very young subcohort.

Mortality

Table 2 shows the observed and expected numbers of deaths for selected causes, using the specific male mortality rates for Parana State as the standard population. Mortality in miners was significantly lower than expected from the general population for all causes of death (SMR = 90, CI = 82–99) and also for all diseases causing death (excluding external causes) (SMR = 88, CI = 79–98). Statistically significant lower mortality estimates were also found for all cancers (SMR = 73, CI = 55–96), chronic respiratory diseases (SMR = 49, CI = 25–95) and digestive system diseases (SMR = 53, CI = 32–87).

Among single cancer sites, only lung cancer presented a non-significant excess of mortality (16 observed vs. 11 expected, SMR = 145, CI = 89–237). Non-significant excesses were found for endocrine, blood and nutritional diseases, specifically diabetes and malnutrition, and also for some external causes of deaths such as accidental falls, drowning and suicide. A significant excess mortality for pneumonia, 2.6-fold excess in comparison with male population from Parana state, was found for the total cohort.

Table 3 shows the mortality experience of underground and surface workers. Mortality for all causes was statistically significantly lower than expected among underground workers, whereas it was only slightly lower among surface workers. It should be pointed out that the non-significant excess of mortality for mal-nutrition and external cause of death (mainly due to drowning and suicide) in underground workers probably reflects the social–economic condition of this group.

A significant deficit of mortality was also found for all cancers, chronic respiratory diseases and digestive system diseases among underground workers, whereas a non-significant deficit was observed among surface workers. Deaths from tuberculosis (three deaths) occurred only among underground workers, with a non-significant excess of mortality.

Mortality from pneumonia was equally above expectation between surface and underground workers, with a significant threefold excess among surface workers and a 2.5-fold excess for underground workers. Although mortality from all cancers was lower than expected among underground workers, lung cancer mortality was significantly increased among underground workers, whereas a non-significant deficit was observed among surface workers.

Lung cancer and pneumonia, which occur in excess when compared with the general population, were analyzed further with respect to the duration of exposure (underground employment duration), period of hire and time since first exposure.

Table 4 presents the SMRs for mortality from lung cancer and pneumonia for four different exposure groups: not exposed group (surface workers), less than 5 years, 5–10 years and more than 10 years of underground exposure duration. Standardized mortality

Table 1 Characteristics of the study population stratified by hiring employment subcohorts, 1942–1997

	Mine employment starting periods			
	1942–1969 (A)	1970–1981 (B)	1982–1997 (C)	Total
Number of miners	706 (100%)	919 (100%)	1,231 (100%)	2,856 (100%)
Underground	526 (74%)	685 (74%)	813 (66%)	2,024 (71%)
Surface	180 (26%)	234 (26%)	418 (34%)	832 (29%)
Person-years	13,860	19,448	15,680	48,991
Mean age at admission (years)	25.7 ± 7.6	26.9 ± 8.7	25.3 ± 7.9	25.9 ± 8.2
Mean duration of employment (years)	7.5 ± 6.9	6.0 ± 4.8	4.6 ± 3.9	5.8 ± 5.2
Percentage alive at the end of follow-up (%)	53	76	91	77
Percentage in activity at the end of follow-up (%)	0.1	0.5	14.5	6.5
Attained age (years)	65.0 ± 9.9	51.0 ± 9.5	38.8 ± 8.7	49.1 ± 13.9

ratios for lung cancer tend to increase with duration of exposure, reaching statistical significance for the category with duration of exposure greater than 10 years (SMR = 269; CI = 120–598), and a statistically significant positive trend was found.

An increased mortality from pneumonia was observed for both surface and underground workers. There was no evident dependence on duration of exposure, and a significant mortality risk was found among underground workers with 5–10 years of employment. For surface workers, a statistically significant pneumonia mortality risk was observed only in those who worked for less than 5 years (SMR = 477, CI = 198–1148). For other duration of exposure categories, the SMR was null since there were no deaths observed (data not shown).

Table 5 presents lung cancer mortality risk depending on duration of exposure among underground

Table 2 Standardized mortality ratios and 95% confidence intervals by specific cause of death among coal miners of Figueira, Brazil, 1979–2002

International classification of diseases		Cause of death	Obs	Exp	SMR (95% CI)
ICD-9	ICD-10				
001–999	A00–Z99	All causes	437	487.4	90 (82–99)
001–139	A00–B99	Infectious and parasitic diseases	12	18.2	66 (37–116)
010–018	A15–A19	Tuberculosis	3	3.5	85 (27–263)
140–239	C00–D48	All cancers	52	71.3	73 (55–96)
150	C15	Esophagus	4	7.2	55 (21–148)
151	C16	Stomach	11	11.9	92 (51–166)
153–154	C18–C21	Colon, rectum, anus	1	4.3	23 (3–165)
161	C32	Larynx	1	2.9	34 (48–245)
162	C33–C34	Trachea, bronchi, lung	16	11.0	145 (89–237)
185	C61	Prostrate	2	5.1	39 (9–155)
204–208	C91–C95	Leukemia	1	2.5	39 (5–278)
240–289	D50–E90	Endocrine and blood diseases	19	14.8	128 (82–201)
250	E10–E14	Diabetes	15	13.1	114 (69–190)
260–269	E40–E46	Malnutrition	2	1.6	122 (30–488)
390–459	I00–I99	Cardiovascular diseases	167	165.8	100 (86–117)
401–405	I10–I15	Hypertensive disease	12	11.9	102 (56–176)
410–414	I20–I25	Ischemic heart disease	59	60.2	97 (76–126)
430–438	I60–I69	Cerebrovascular disease	61	66.1	71 (71–118)
460–519	J00–J99	Respiratory systems	36	35.6	100 (73–139)
480–486	J12–J18	Pneumonia	16	6.1	263 (160–429)
490–493	J40–J47	Chronic respiratory diseases	9	18.2	49 (25–95)
520–579	K00–K93	Digestive system	16	29.9	53 (32–87)
571	K70–K77	Liver chronic disease and cirrhosis	9	16.2	55 (28–106)
580–629	N00–N99	Genital urinary diseases	4	5.5	72 (27–192)
780–799	R00–R99	Ill-defined causes	43	51.7	83 (61–110)
800–999	S00–Y98	External causes	85	79.9	106 (86–112)
800–848	V01–V99	Transport accident	27	33	81 (55–118)
850–888	W00–W19	Accidental falls	4	3.7	106 (39- 282)
910	W65–W74	Drowning	5	3.7	133 (55–321)
950–959	X60–X84	Suicide	9	7.5	120 (63–231)
960–969	X85–Y09	Homicide	17	19	88 (54–141)

Obs observed deaths, *Exp* expected deaths according to male mortality data, State of Parana Health Office

Table 3 Standardized mortality ratios and 95% confidence intervals by specific cause of death among coal miners of Figueira, Brazil, 1979–2002: comparison between surface and underground workers

Cause of death	Surface workers			Underground workers		
	Obs	Exp	SMR (95% CI)	Obs	Exp	SMR (95% CI)
All causes	124	129.6	96 (80–114)	313	356.4	88 (78–98)
Infectious and parasitic diseases	4	4.8	83 (31–220)	8	13.4	59 (30–119)
Tuberculosis	0	1	0	3	2.6	114 (37–355)
All cancers	15	18.6	80 (48–134)	37	52.7	70 (51–97)
Esophagus	0	1.8	0	4	5.3	75 (28–200)
Stomach	3	3.1	96 (30–297)	8	8.7	91 (45–182)
Colon, rectum, anus	1	1.1	89 (12–634)	0	3.1	0
Larynx	0	0.7	0	1	2.1	47 (6–331)
Trachea, bronchi, lung	2	2.8	69 (17–279)	14	8.1	173 (102–292)
Prostrate	0	1.3	0	2	3.8	53 (13–211)
Leukemia	0	0.7	0	1	1.8	53 (7–380)
Endocrine and blood diseases	7	3.9	180 (86–378)	12	10.9	109 (62–193)
Diabetes	7	3.7	189 (90–397)	8	9.6	83 (41–166)
Malnutrition	0	0.43	0	2	1.2	165 (41–661)
Cardiovascular diseases	48	43.5	110 (83–146)	119	122.5	97 (81–116)
Hypertensive disease	6	3.1	191 (86–426)	6	8.7	68 (30–152)
Ischemic heart disease	10	16	63 (34–118)	49	42.3	116 (87–153)
Cerebrovascular disease	20	17.3	115 (74–178)	41	46.3	88 (65–120)
Respiratory systems	11	9.3	119 (66–214)	25	26.4	94 (64–139)
Pneumonia	5	1.6	304 (126–730)	11	4.3	253 (140–457)
Chronic respiratory diseases	4	4.7	84 (31–225)	5	13.4	37 (15–89)
Digestive system	3	7.7	39 (12–120)	13	22.2	58 (34–100)
Liver chronic disease and cirrhosis	2	4.17	48 (12–191)	7	12.0	58 (27–122)
Genital urinary diseases	0	1.5	0	4	4.08	98 (37–261)
Ill-defined causes	12	13.9	93 (54–160)	31	37.9	82 (57–116)
External causes	23	23.2	86 (49–151)	62	57.5	107 (84–138)
Transport accident	8	9.5	83 (42–167)	19	24	79 (51–124)
Accidental falls	1	1.02	97 (14–693)	3	2.7	109 (35–340)
Drowning	1	1.16	86 (12–614)	4	2.6	151 (57–404)
Suicide	2	2.1	93 (23–375)	7	5.4	129 (62–272)
Homicide	4	5.8	69(26–184)	13	13.6	95 (55–164)

workers stratified into three categories by time since first exposure: < 10 years, 10–30 years and > 30 years. In the category < 10 years, the SMR value was not calculated since the expected number of cases is almost zero (0.04). This would yield an inconsistent SMR value. Since for an occupational etiology of lung cancer a minimum latency period of 10 years is assumed, the only two cases of death that occurred within the first 10-years interval were probably not related to workplace exposure.

From 10 to 30 years since first exposure, the SMR increased with duration of exposure with a statistically significant trend. The risk seems, however, to decrease with time since exposure, as is seen by a comparison between the categories 10–30 years and > 30 years.

Concerning the analyses by subcohorts based on period of hire, we considered only two subcohorts: miners hired before and after 1970. This was due to the small number of lung cancers to be stratified. Table 6 presents lung cancer mortality risk by period of hire. Miners starting employment after 1970 exhibit increased lung cancer mortality with a significant trend with duration of exposure. Ten lung cancer deaths occurred against only 2.4 expected. These 10 lung cancer deaths occurred among miners hired between 1970 and 1980. For miners hired before 1970, 4 lung cancers deaths occurred against 5.5 expected. This may suggest a bias caused by the great proportion of workers with unknown vital status (24%) among this subcohort, which were excluded from the analysis.

Table 4 Observed and expected numbers of death, SMR and 95% CI for lung cancer and pneumonia cause of death by duration of exposure—coal miner cohort, Figueira, 1979–2002

Cause of death	Duration of exposure	Person-years	Observed/expected	SMR (95% CI)	RR	Test for trend (p value)
Lung cancer	Not-exposed [a]	14,167	2/2.8	69 (17–279)	1.0	0.03
	< 5 years	21,127	3/3.6	83 (27–258)	1.20	
	5–10 years	8,111	5/2.3	215 (90–518)	3.11	
	> 10 years	5,585	6/2.2	269 (120–598)	3.89	
Pneumonia	Not-exposed [a]	14,167	5/1.6	304 (126–730)	1.0	0.99
	< 5 years	21,127	4/2.1	192 (72–514)	0.63	
	5–10 years	8,111	4/1.3	307 (115–817)	1.01	
	> 10 years	5,585	3/1.1	277 (89–859)	0.91	

[a] Surface workers

Table 5 Observed and expected numbers of lung cancer, SMR and 95% CI by time since first exposure and duration of exposure for underground workers—Coal miner cohort, Figueira, 1979–2002

Time since exposure (years)	Duration of exposure (years)	Person-years	Observed/expected	SMR (95% CI)	Total SMR
< 10	< 5	1,883	0/0.03	0	NA
	5–10	219	2/0.01	NA	
	> 10	–	0/0	0	
10–30	< 5	14,273	2/1.1	182 (45–727)	458* (246–851)
	5–10	5,107	3/0.7	434 (140–1,347)	
	> 10	2,442	5/0.4	1,269 (528–3,050)	
> 30	< 5	4,970	1/2.5	40 (6–287)	33 (8–134)
	5–10	2,784	0/1.6	0	
	> 10	3,143	1/1.8	54 (7–386)	

NA not applicable (no expected cases)
*Test for trend, *p* value = 0.009

When evaluating the influence of period of hiring and exposure duration on the risk of pneumonia mortality, a significant excess mortality risk was found for the 1970–1997 period of hire (SMR = 292, CI = 152–562) and a non-significant excess mortality risk was found for workers hired before 1970 (SMR = 144, CI = 36–577). No dependence on duration of exposure was observed.

Discussion

In the present study the mortality of Figueira coal miners exposed to radon and radon daughters at underground work environment was investigated. The major finding of this study is a significant excess risk of lung cancer among underground workers and an observed increase of risk with increasing duration of exposure (years worked underground). Contrary to lung cancer, the risk of mortality from pneumonia seems to be unrelated to underground exposure, since the observed increase in pneumonia SMR was seen in surface and underground coal miners. The reason for the enhanced pneumonia SMR is not clear. It is possible that pneumonia was underreported in the general population of the state of Parana, thus yielding an apparently increased SMR for this condition among the coal miners. It is noteworthy to mention that mortality for all respiratory diseases among the studied coal miners cohort is quite similar to that expected (SMR = 100 for all cohort, SMR = 119 in surface and SMR = 94 in underground workers). Remarkably, no case of death was related to silicosis, which could have been included in the group of chronic respiratory diseases presented in Table 2.

The observation of reduced mortality from all causes in mine workers may be explained by the healthy-worker effect. This can even better be seen in terms of mortality from all causes of diseases (excluding external causes of death), since the working population comprises individuals necessarily healthy enough to be employable and whose mortality risk is therefore initially lower than that observed in the general population. Working populations typically present a mortality risk ranging 60–90% to that of the general population [39]. However, the significant reduction in mortality from all cancers observed among miners is not consistent with other observations of the healthy-worker effect, where cancer is usually affected to a lower degree than other chronic conditions [31, 39].

It cannot be excluded from the fact that this deficit is due to a lack of complete information of vital status of the 110 subjects who were known to be alive at any period between 1979 and 1997. Two hypotheses can be considered to evaluate the effect of this missing information: if the 110 subjects were dead at the time they were lost to follow-up and if their deaths showed the same distribution as the 438 recorded deaths, the SMR for all causes of death would be increased by about 23% (SMR = 111, CI = 102–121) and no healthy-worker effect would have been observed. Otherwise, if those subjects were considered to be alive at the end of the follow-up period, a lower SMR value of 83 (CI = 75–91) would be obtained, indicating a significant deficit for

Table 6 Observed and expected numbers of lung cancer and pneumonia cause of death, SMR and 95% CI by period of hire and duration of exposure for underground workers—coal miner cohort, Figueira, 1979–2002

Cause of death	Period of hire	Duration of exposure (years)	Obs/Exp	SMR (95% CI)	Total SMR (95% CI)
Lung cancer	1942–1969	< 5	2/2.4	82 (20–327)	69 (26–186)
		5–10	0/1.5	0	
		> 10	2/1.7	113 (28–452)	
	1970–1997	< 5	1/1.1	86 (12–613)	412* (222–766)
		5–10	5/0.8	622 (259–1496)	
		> 10	4/0.5	866 (323–2295	
Pneumonia	1942–1969	< 5	4/1.3	317 (118–844)	292 (152–562)
		5–10	3/0.9	323 (106–1023	
		> 10	2/0.9	221 (55–884)	
	1970–1997	< 5	0/0.8	0	144 (36–577)
		5–10	1/0.4	253 (35–179)	
		> 10	1/0.2	562 (79–399)	

*Test for trend, *p* value = 0.025

all causes of death in comparison with the general male population mortality risk. The hypothesis of them being alive is probably more plausible, since these subjects were exhaustively searched in the death database of the Health Office of Parana, but no records were found. It would be improbable that deaths occurred outside Parana State, since among all deaths registered in the cohort, 88% occurred in Parana State, against 9% in São Paulo State and 3% in other Brazilian states.

It should also be taken into account that the choice of 22 October 2002 (Brazilian polls), as the end of the follow-up period, yields, to some degree, a misevaluation of the total workers person-years exposure, since the months of November and December 2002 were not included. Nevertheless, we believe that such underestimation will introduce, as a whole, minor errors on SMR ascertainments.

An increased mortality risk of lung cancer was found for underground workers, and a strong relationship with duration of underground employment. In interpreting the results of this study, some limitations must be kept in mind. The most important limitation of the present study is the lack of exposure quantification due to the unavailability of cumulative radon exposure estimate. Assessment of exposure is a key condition for ascertaining differential health outcomes in non-concurrent occupational cohorts, such as the miners, followed up in this study. We used underground employment duration as a surrogate of overall exposure rather than using other procedures, such as classifying the different job activities according to high or low radon exposure. In this study, a complete record of the specific past activities carried out by mine workers was unavailable, hampering such strategy. Therefore, underground employment duration was considered as the most appropriate surrogate considering local available data.

The major potential confounder in any association with lung cancer is, of course, smoking. It has been reported that smoking habits of manual workers in general differ from those of the general population [38]. Since smoking information of cohort members was not available, it is necessary to rely on indirect evidence. Other authors used the SMR for cancer sites presumably related to smoking, other than lung cancer, to evaluate the confounding effect of smoking on the risk estimate for lung cancer [3]. Mortality from smoking-related cancers (i.e., cancers of larynx, esophagus, oral cavity and bladder) was not found elevated in underground workers. No cases of death from mouth and bladder cancer were observed nor was there an excess of chronic respiratory diseases. These data indirectly suggest that smoking is unlikely to bias the present results greatly.

In conclusion, radon is a likely agent responsible for the increased lung cancer risk observed in underground miners, although duration of exposure is a poor surrogate for exposure to radon and its decay products. The trend toward increases in the SMRs and RRs with duration of exposure may indeed be caused by exposure to radon and its decay products, but it could be argued that there are other lung carcinogenic contaminants possibly present in the work environment, such as silica-containing dusts, heavy metals, arsenic, etc. In the present study it was not feasible to distinguish between the effects of exposure to radon and radon daughters and all other lung carcinogenic contaminants possibly present in the work environment. Only diesel fumes could be ruled out because diesel equipment has not been used in this mine.

Nevertheless, it should be taken into account that significant evidence exists both from epidemiologic studies and animal studies [40] for an increased risk of lung cancer associated to radon and radon daughters. No such evidence has been presented for exposure to coal dust or the other contaminants possibly present in underground environment of coal mines. Concerning thoron, no measurements were available. After inhalation of thoron daughters, tissues in the bone surfaces and the kidney are considered to be at great risk, together with lung tissues. This situation is in contrast to inhalation of radon daughters, where only the lung is considered to be at risk [8]. In the present study group, no bone or kidney cancer was found. This finding suggests that thoron daughters have contributed relatively little or not at all to the radiation hazard among the underground workers. We therefore conclude that among the various lung carcinogenic agents possibly present in the coal mine underground environment, radon and radon daughters exposure, which indeed were ascertained in this coal mine, are the most likely candidates for a causal association with lung cancer.

Similar conclusions can be drawn when comparing the results of our study with other epidemiological studies on underground coal miners which were exposed to low levels of radon, but the same potential contaminants in the environment [2, 11–18]. In these studies, no excess of lung cancer was found. On the other hand, among underground coal miners in Poland which work under conditions of short-lived radon progeny hazard, an increased risk of lung cancer (diseases and deaths) was observed. Maximum values of potential alpha energy concentration of short-lived radon progeny at these Polish mines were 2.5 μJ m^{-3} (0.12 WL) [32]. An increased risk for lung cancer was also observed among American coal miners [41], but this study used data derived from decennial census counts of coal miners combined with counts of death certificates. In addition, only occupation information was used, whereas the kind of exposures and possible causal agents were not given. A study of cancer mortality among retired railway workers in relation to diesel fume and coal dust suggested that the diesel fumes exposure would be responsible for an increased lung cancer risk among these workers [10].

Although our study has demonstrated an increase in the lung cancer mortality for underground workers, with a significant dependence between increase and duration of employment, the observed number of lung cancer deaths is relatively small with the current follow-up, limiting the analysis for modifying variables, such as time since first exposure and period of hire. While in this study the cumulative radon exposure has not been quantified or estimated, the mortality risk for lung cancer could be determined. Therefore, if we assume a simple model for the RR with WLM as $RR = 1 + 0.012 \times WLM$ [42], the radon exposure consistent with the observed RRs can be estimated. For miners at the highest category of exposure duration that presented a statistically significant RR (approximate duration 15 years, RR = 4), radon progeny annual exposure level would be around 17 WLM. On the other hand, if we assume a more conservative approach, for instance, taking into account a RR = 1.4 observed among workers employed for less than 5 years (Table 4), we would obtain an annual exposure estimate of 11.7 WLM. Both estimates are higher than the maximum estimated radon exposure of 7 WLM $year^{-1}$, possibly indicating that radon exposure in the past was about twofold higher than the recently measured value in the mine environment.

Although such an approach is unusual in epidemiological studies, it can be seen as an alternative approach to give an idea of the past exposure, if it is assumed that the true lung cancer radon risk was determined. There are, however, many uncertainties in doing this and the discussion of which is beyond the scope of the present paper.

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