Mortality in uranium miners in West Bohemia: a long term cohort study

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Abstract

A cohort of 4320 uranium miners in West Bohemia who started work at the mines during 1948 to 1959 and worked there for at least four years were followed up to the end of 1990 to determine cause specific mortality risks in relation to exposures in the mines. The miners had experienced high radon exposures, on average 219 working level months during their uranium mining careers, for which detailed measurements were available. They had also been exposed to high arsenic levels in one of the two major mines, and to dust. New follow up methods, not previously used for occupational cohorts in Czechoslovakia, were utilised. By the end of follow up 2415 (56%) of the cohort were known to have died. Overall mortality was significantly raised compared with that in the general population (relative risk (RR) = 1·56, 95% confidence interval (95% CI) 1·50—1·63), with significantly raised risks of lung cancer (RR = 5·08, 95% CI 4·71—5·47), accidents (RR = 1·59, 95% CI 1·34—1·87), homicide (RR = 5·57, 95% CI 2·66—10·21), mental disorders (RR = 5·18, 95% CI 2·83—8·70), cirrhosis (RR = 1·51, 95% CI 1·16—1·94), and non-rheumatic circulatory diseases (RR = 1·16, 95% CI 1·08—1·25). The relative risk of lung cancer was greatest four to 14 years after entry to the mines. Relative risks for homicide and accidents were raised up to 25 years from entry but not after this. Substantial significantly raised risks at 15 to 24 years after entry occurred for cirrhosis, non-rheumatic circulatory diseases, and pneumonia and other respiratory infections. Sizeable significantly raised risks at 25 and more years after entry, but not earlier, were present for mental disorders, tuberculosis, and non-malignant non-infectious respiratory conditions. No specific causes showed risks significantly related to age at entry to mining. Risk of lung cancer was significantly positively related to radon exposure, estimated arsenic exposure, and duration of work in the mines, but no other cause was significantly positively related to these variables. The raised risk of lung cancer in uranium miners, which is well established, is related aetiologically to radon exposure, and in the present cohort it may also in part have been due to exposure to arsenic. The raised risks of accidents, tuberculosis, and non-infectious respiratory diseases have also been seen in other uranium mining cohorts, and are likely to reflect the dangerous and dusty working conditions and the confined spaces in which work occurred. The cirrhosis and homicide deaths probably relate to the lifestyle associated with mining. The raised risk of circulatory diseases does not seem to be related to radon or arsenic exposure; its causes are unclear. The use of multiple follow up methods was found to be critical to correct ascertainment of mortality in the cohort.

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Mining has been carried out in the Erz mountains, on the border between Czechoslovakia and Germany, for several centuries. In Jáchymov (Joachimsthal), Czechoslovakia, pitchblende was mined for radium before the second world war[1] and uranium was mined during the war by French and other prisoners, and after the war by Czechoslovaks who also mined uranium at Horní Slavkov, 40 km to the south.

High mortality from pulmonary disease in miners in the area has been known since the 16th century.[2] This disease was recognised as cancer in 1879 at Schneeberg on the German side of the frontier.[3] Lung cancer was first reported in the Jáchymov mines in 1929,[4] and soon afterwards was established as a major cause of death in the miners by Pirchan and Šikl,[5] who suggested that radon was the likely cause.

The present cohort was established in 1970. Published analyses have concentrated on cancer risks,[6–9] however, and virtually no data have been published on risks of other causes of death. Information on these causes for certain other radon exposed mining cohorts have found, as well as raised risk of lung cancer[10–16] and in some instances other cancers,[13–15] raised risks of mortality from tuberculosis,[10–12] silicosis,[10–15] other chronic non-malignant lung disease,[10 15] alcoholism,[10] accidents and violence,[10–16] cardiovascular disease, not further specified,[14] rheumatic fever and rheumatic heart disease,[10] heart disease other than rheumatic or atherosclerotic,[10] and chronic nephritis and renal sclerosis.[10] The published analyses from most of these studies for causes other than cancer have been limited, however, and there has been little investigation of risk in relation to variables such as radon exposure and age.

We have now extended the follow up of the West Bohemian cohort, evaluated and improved its completeness, and coded all deaths by cause for the first time. We examine here the mortality from a wide range of causes, and evaluate the relation of mortality risks to radon and arsenic exposures. For completeness in consideration of overall mortality of this group and the balance between different causes, we have included information on lung cancer and other cancer mortality in the same degree of detail as for the non-malignant causes; greater detail and statistical modelling of the cancer risks can be found elsewhere.[8 9]

Materials and methods

COHORT DEFINITION

The cohort was established by a search in 1970 of employment records for 95 000 miners at Jáchymov and Horní Slavkov, of whom 40 364 were identified as having worked underground in 1948 or later. From these underground workers, men were included in the cohort if they satisfied the following criteria: (*a*) underground work commenced in 1948–59; (*b*) underground work lasted at least four years (subsequent checks showed that 19 miners initially included actually worked for slightly shorter periods (3·6–3·9 years); these men have been retained in the present analysis); and (*c*) personnel and employment records were available, including details of duration of underground employment and time spent in each shaft.

It is likely that few miners were excluded because they had started work in the mines before 1948. The main reason for exclusion was that there were many short term workers because of high wages and poor working conditions. A few men were excluded because of inadequate information in their employment record, but it is thought unlikely that records had been removed or become incomplete because of death or emigration before 1970.

The final cohort that met the entry criteria consisted of 4320 men. Most were Czechs, about 25% were Slovaks and 5% had German ancestry. Few had other igneous rock mining experience: under 2% had mined non-uranium ores before they mined uranium, and under 1% had 10 or more years such experience.[6]

When the cohort was identified in 1970, the mines had already closed and so information on the smoking habits of the men could not be obtained. A survey of 697 men in other Czech uranium mines in 1974, however, showed that 76% were smokers,[17] somewhat more than the male average for Czechoslovakia in the early 1970s (66%).[18] Smoking was permitted in the mines until 1962.

METHOD OF FOLLOW UP

The follow up before 1975 was aimed primarily at ascertaining lung cancers from occupational, death registration, and clinical sources. The cohort was also checked against the Central Czech and Slovak cancer registries. Although some other deaths were discovered among current employees or from the cancer registries, deaths from other causes were not ascertained systematically. Any deaths missed during this period should, however, have been ascertained in 1975, when the vital status of the cohort was checked against the population register at the Ministry of the Interior. Further such checks were carried out in 1980, 1985, and 1990. These checks provided information on dates of death and emigration, but did not give a positive check on vital status, and many deaths were missed. For the present analysis follow up has been to 1 January 1991, and we have employed methods not used previously to reduce the number of missing deaths. Firstly, we checked cohort names against files at the Pensions Offices of the Czech and Slovak Ministries of Social Security. Then, for men not shown as currently receiving a pension or dying in years for which the pensions files have retained records of deceased men, we tried to ascertain vital status by direct correspondence and local enquiries.

For most deaths before 1975 that were ascertained from occupational and cancer registration sources, these sources also provided information on the underlying cause of death. For other deaths, the cause of death was obtained where possible from local death registers, or failing this from local health care facilities or the death certificate held by the family. The cause of death was coded to the International Classification of Diseases (ICD) eighth revision[19] for deaths before 1979 and ninth revision[20] for deaths thereafter.

EXPOSURE ESTIMATES

Extensive radon exposure data were available from 39 000 measurements of radon gas concentrations taken underground during 1949 to 1963 at Jáchymov and Horní Slavkov, which until the mid-1950s were the major uranium mines in Czechoslovakia, and also at other uranium mines in the country to which some of the men moved, particularly after most shafts at Jáchymov and Horní Slavkov closed in 1963. The exposure estimates have been completely revised (Tomášek *et al*, unpublished data), with correction of previous errors, for the present analysis. An estimate of the exposure received by each man in each year of his employment at the mines in terms of working level months (The working level (WL) is defined as any combination of radon daughters in 1 litre of air that will result in the estimated emission of $1{\cdot}3 \times 10^5$ MeV potential alpha energy. Exposure of a miner to this concentration for 170 hours (or twice this concentration for half as long, etc) is defined as a working level month (WLM).) was calculated by considering the shifts that he spent in each mine shaft in conjunction with the estimated annual concentration of radon daughters in each shaft. Appropriate adjustments were made for annual holidays and for the exposures of workers such as geologists who were unlikely to have spent all of each shift underground and exploratory workers who

worked mainly in shallow shafts near the surface.

There was relatively little dust in the mines, as wet drilling had been introduced before the second world war: dust levels at Jáchymov and Horní Slavkov are believed to have been up to about 10 mg/m^3 in the early years of the present study and lower in the later years, with levels under 2 mg/m^3 from 1958.[21] All artificial ventilation was carried out with electric motors; no diesel engines were used. There were only "trace amounts" of chromium, nickel, and cobalt in the mine dust.[22] Arsenic levels were much greater in Jáchymov (mean percentage of arsenic in the dust 0·5%, maximum 7·1%) than Horní Slavkov (mean 0·01%, maximum 0·053%).[23] Because of this difference between the mines we recoded the occupational histories to score each miner's arsenic exposure, on the basis of the limited data available about arsenic and dust levels in the mines, as 1 for each year worked underground at Jáchymov before 1958, 0·33 for each year worked underground at Jáchymov from 1958 onwards, and zero for work at all other mines.

METHOD OF ANALYSIS

Person-years at risk were calculated for each man, starting at four years after entering employment at the mines and ending at the earliest of date of death, emigration, 85th birthday, loss to follow up, or 1 January 1991. Because uranium mining was well paid, it attracted workers from all over Czechoslovakia, and after closure of the mines many of the men moved away from the locality; we therefore used national rather than local mortality data for calculation of expected deaths. Annual national death rates by five year age group for 1953–90 were obtained from the World Health Organisation and Czechoslovak Federal Statistical Office, and we bridge coded them to the same ICD revisions as for the miners' data. Estimates of the national death rates by single year of age were made by interpolation. For each cause of death, the expected numbers of deaths were then calculated by multiplying the single year of age and calendar year specific person-years at risk by the estimated national death rates for the corresponding age and year. Confidence intervals and two sided p values for the observed to expected ratios were calculated from the Poisson distribution.

Mortality risks were also analysed by cumulated radon and arsenic exposures. These analyses were conducted (*a*) for total cumulative exposure; (*b*) lagging the radon and arsenic exposures by five, and by 10 years: we excluded deaths and person-years of observation in the first 10 years after initial employment from these analyses, to allow the healthy worker selection effect[24] to wear off, (*c*) considering only exposures during the past 10 years, as the aetiological effects of radon or arsenic might wear off after this time.

Analyses were also performed in relation to duration of employment in the mines. We restricted these analyses to person-years 15 and more years after first employment in men who had worked for less than 15 years, so that the employment and follow up periods should not overlap.[25] Otherwise, deaths during employment would necessarily have led towards an association of mortality with short employment durations.

Tests for trend in mortality were carried out with likelihood ratio tests. For the radon and arsenic analyses the data were divided into five exposure categories such that the numbers of expected deaths in each category were about equal. For the duration of employment analyses the data were divided into four roughly equal categories.

Results

By the end of the study period 55·9% (2415) of the study cohort were known to have died (table 1), 314 emigrated, 43 were lost to follow up because they could not be traced in the Ministry of the Interior records, and 1548 had records in the Ministry indicating that they were alive in Czechoslovakia on 31 December 1990. For 1512 (97·7%) of these 1548 cases, we also had evidence from pensions files or direct correspondence that they were alive in Czechoslovakia. Twenty seven of the cohort members were censored from follow up at age 85: 14 are known to have died subsequently but before the follow up date, seven of atherosclerosis, and seven of other causes. In total 106 983 person-years at risk accumulated in the study: an average of 24·8 years per man.

Most of the miners started work in the mines at ages 20–39 (68·6%), with few employed before age 20 (7·6%) (table 2). Most (55·2%) worked underground for five to nine years, and only 3·9% worked for 15 years or more. The average final cumulative radon exposure was 219 WLM. Most of the miners had cumulative exposures in the range 100 to 299 WLM (62·8%). Only two men had been exposed to 1000 WLM or more. Mean radon concentrations during underground employment careers were mainly between 1 and 3 WL; annual average exposures decreased from 87 WLM in 1948 to 17 WLM in 1960 and under 3 WLM from 1970 onwards.

The relative risk (RR) of all cause mortality in the cohort compared with the general Czechoslovak population was 1·56 (95% CI 1·50—1·63) (table 3). There were no deaths in cohort members less than four years after starting employment because of the entry criteria to the cohort. Risk was substantially

Table 1 Vital status of study cohort on 1 January 1991

Status	*No of men (%)*
Died:	
Cause of death obtained	2374 (55·0)
Unknown cause of death	41 (0·9)
Emigrated	314 (7·3)
Lost	43 (1·0)
Alive and living in Czechoslovakia	1548 (35·8)
Total	4320 (100·0)

Table 2 Numbers of men by age at start of employment, duration of employment underground, cumulative exposure to radon at end of employment, average radon concentration during employment underground, and estimated cumulative exposure to arsenic at end of employment

	No of men (%)
Age at start of employment (y):	
<20	330 (7·6)
20–29	1760 (40·7)
30–39	1205 (27·9)
40–49	825 (19·1)
⩾50	200 (4·6)
Duration of exposure (y):	
3–4	877 (20·3)
5–9	2385 (55·2)
10–14	887 (20·5)
15–19	165 (3·8)
⩾20	6 (0·14)
Cumulative radon exposure on termination of employment (WLM):	
<50	125 (2·9)
50–99	573 (13·3)
100–199	1838 (42·6)
200–299	872 (20·2)
300–399	373 (8·6)
400–499	264 (6·1)
500–599	147 (3·4)
600–699	65 (1·5)
⩾700	63 (1·4)
Average radon concentration during employment underground (WL):	
<1·0	224 (5·2)
1·0–1·9	1408 (32·6)
2·0–2·9	1562 (36·2)
3·0–3·9	576 (13·3)
4·0–4·9	293 (6·8)
⩾5·0	257 (5·9)
Estimated cumulative arsenic exposure on termination of employment*:	
0	1292 (29·9)
1–4	1467 (34·0)
5–9	1383 (32·0)
⩾10	178 (4·1)
Total number of men	4320 (100·0)

*See text for description of units

raised, however, 4–14 years after first employment (table 3), reached a peak at 15–24 years (RR = 1·80, 95% CI 1·68—1·93), and then decreased to an RR of 1·43 (95% CI 1·35—1·51) at 25 and more years after first employment. The raised risk in the cohort resulted primarily from raised risks of lung cancer (RR = 5·08, 95% CI 4·71—5·47), for which the RR was greatest at 4 to 14 years after first employment and then diminished (In five-year groupings (not shown) the peak RR was 9·17 (95% CI 7·50—11·10) at 10-14 years after first employment, with a steady decrease thereafter), and accidents (RR = 1·59, 95% CI 1·34—1·87), for which the RR was raised substantially up to 24 years from first employment, but much less thereafter. There were also substantial significantly raised risks for the follow up period overall for homicide (RR = 5·57, 95% CI 2·66—10·21), for which all deaths were before 25 years from first employment; mental disorders (RR = 5·18, 95% CI 2·83—8·70), resulting solely from deaths 25 or more years after first employment, six of which were certified to alcoholism; and cirrhosis (RR = 1·51, 95% CI 1·16—1·94), which reflected mainly an increased risk 15 to 24 years after first employment. Similar patterns to that for cirrhosis were seen for non-rheumatic circulatory diseases, for which risk was significantly but slightly raised overall (RR = 1·16, 95% CI 1·08—1·25), with greater risk at 15 to 24 years after first employment (RR = 1·32, 95% CI 1·15—1·50), and pneumonia and other respiratory infections, for which risk was significantly raised 15 to 24 years after first employment, but not overall.

There were significantly raised risks more than 25 years after first employment but not previously for tuberculosis and for

Table 3 Observed deaths (O) and ratio of observed to expected deaths (O/E) at ages less than 85 years by cause and time since first employment

	Time since first employment							
	4†-14 years		*15-24 years*		*⩾25 years*		*All years*	
Cause of death (ICD-9)	*O*	*O/E*	*O*	*O/E*	*O*	*O/E*	*O*	*O/E*
Tuberculosis (010–018)	8	0·64	3	0·56	8**	3·54	19	0·94
Lung cancer (162)	142***	7·66	275***	7·03	287***	3·55	704***	5·08
Other malignant neoplasms (140–208 excluding 162)	38	0·86	89	1·18	165	1·14	292	1·11
Mental disorders (290–319)	0	0·00	0	0·00	14***	8·76	14***	5·18
Rheumatic fever and rheumatic heart disease (390–398)	2*	0·27	5	0·69	6	1·05	13	0·64
Other circulatory diseases (399–459)	86	1·12	238***	1·32	455*	1·10	779***	1·16
Pneumonia, influenza, and other acute respiratory infections (460–466, 480–487)	2	0·39	19**	1·97	24	1·17	45	1·27
Other respiratory diseases (470–478, 490–519)	12	1·12	19	0·73	60**	1·58	91	1·21
Cirrhosis of liver (571)	6	1·35	29***	2·20	27	1·15	62**	1·51
Other digestive diseases (520–579 excluding 571)	6	0·82	16	1·31	15	0·76	37	0·94
Urinary diseases (580–629 excluding 600)	5	0·94	5	0·57	13	0·83	23	0·77
Suicide (E950–E959)	24	1·32	15	0·89	21	1·47	60	1·22
Homicide (E960–E969)	5**	6·45	5***	8·61	0	0·00	10***	5·57
Accidents (E800–E999 excluding E950–E969)	56***	1·77	50***	1·75	39	1·25	145***	1·59
Other known causes	13	0·92	11	0·69	42*	1·49	66	1·13
Unknown cause	9	—	12	—	20	—	41	—
All known causes, except for malignant neoplasms, accidents, and violence	140	0·97	345***	1·24	664***	1·17	1149***	1·16
All causes	414***	1·61	791***	1·80	1196***	1·43	2401***	1·56

*p < 0·05; **p < 0·01; ***p < 0·001 (two sided test that the difference between the number of deaths observed and that expected could have occurred by chance.
†By definition of the study cohort, the workers had survived to four years from commencement of employment (see materials and methods).

Table 4 Observed deaths (O) and ratio of observed to expected deaths (O/E) at ages under 85 years by cause and age at first employment

	Age at first employment (y)					
	<25		25–34		⩾35	
Cause of death	O	O/E	O	O/E	O	O/E
Tuberculosis	2	0·92	6	1·07	11	0·89
Lung cancer	110***	5·26	257***	5·11	337***	5·00
Other malignant neoplasms	54**	1·51	82	0·92	156	1·12
Mental disorders	6***	7·47	1	0·88	7***	9·19
Rheumatic fever and rheumatic heart disease	3	0·75	3	0·39	7	0·80
Other circulatory diseases	70	0·92	269***	1·26	440**	1·16
Pneumonia, etc	3	0·78	12	1·20	31	1·39
Other respiratory diseases	11	1·85	28*	1·52	52	1·03
Cirrhosis of liver	8	0·87	34***	2·01	20	1·34
Other digestive diseases	4	0·67	13	0·98	20	0·99
Urinary diseases	3	0·67	7	0·71	13	0·85
Suicide	10	0·75	35**	1·78	15	0·91
Homicide	5***	8·87	4**	5·28	1	2·11
Accidents	47***	1·88	52**	1·47	46*	1·48
Other known causes	7	0·89	23	1·25	36	1·12
All known causes except malignant neoplasms, accidents, and violence	117	0·98	395***	1·26	637**	1·14
All causes	350***	1·62	842***	1·66	1209***	1·49

*p < 0·05; **p < 0·01; ***p < 0·001 (two sided test that the difference between the number of deaths observed and that expected could have occurred by chance).

non-infectious respiratory conditions. Examining the years and shafts in which the 19 men who died of tuberculosis had worked, 11 were potentially contacts in one chain: two subjects had worked in the same shaft (out of the 47 shafts in the mines) in 1949–50, and each had subsequently worked in another shaft with three further cases; one of whom then gave potential links to three more cases.

The RR for all cause mortality was slightly higher for men who started work in the mines under age 35 than for those who entered at older ages (table 4), and the trend in risk with age at entry was significant (p = 0·025). There was no significant trend, however, for any specific cause, although for lung cancer, homicide, accidents, and non-infectious respiratory diseases, there was a tendency to greater RRs at younger age of first employment, and for non-lung malignancies risk was significantly raised for men first employed before age 25 but not at older ages.

Relative risks of lung cancer and homicide were much greater at young than at older attained ages (linear trend p < 0·001 for lung cancer, p < 0·05 for homicide) (table 5). Absolute excess risks of lung cancer increased with age, but of homicide decreased with age. The only other causes with significant relations of RR to attained age were accidents, for which RRs decreased with age (p < 0·05), and tuberculosis (p < 0·05) and mental disorders (p = 0·001), for which RRs increased with age.

Cumulative radon exposure with a five year lag period (table 6), was significantly positively associated with all cause mortality, because of a highly significant relation with lung cancer, and was significantly negatively associated with suicide mortality. Similar results were obtained with no lag period or a

Table 5 Observed deaths (O) and ratio of observed to expected deaths (O/E) at ages under 85 years by cause and attained age

	Age(y)							
	<45		45–54		55–64		⩾65	
Cause of death	O	O/E	O	O/E	O	O/E	O	O/E
Tuberculosis	0**	0·00	7	1·15	9	1·47	3	1·09
Lung cancer	60***	16·48	215***	8·30	277***	4·42	152***	3·27
Other malignant neoplasms	12	0·79	54	1·08	113	1·10	113	1·17
Mental disorders	0	0·00	1	1·37	6**	5·34	7***	15·21
Rheumatic fever and rheumatic heart disease	2	0·43	4	0·62	4	0·62	3	1·04
Other circulatory diseases	26	1·10	126*	1·26	262	1·11	365**	1·18
Pneumonia, etc	0	0·00	6	1·14	18*	1·75	21	1·17
Other respiratory diseases	1	0·49	13	1·31	38*	1·45	39	1·06
Cirrhosis of liver	2	0·76	21*	1·86	30**	1·71	9	0·94
Other digestive diseases	3	0·84	7	0·82	14	1·02	13	0·97
Urinary diseases	1	0·33	6	1·02	7	0·71	9	0·82
Suicide	15	0·99	21	1·28	16	1·37	8	1·32
Homicide	7***	9·72	2	3·59	1	2·71	0	0·00
Accidents	50***	1·80	46***	1·83	33	1·42	16	1·05
Other known causes	5	0·79	12	1·06	18	0·92	31*	1·47
All known causes except malignant neoplasms, accidents, and violence	40	0·75	203**	1·23	406**	1·17	500***	1·18
All causes	190***	1·64	549***	1·94	859***	1·57	803***	1·36

*p < 0·05; **p < 0·01; ***p < 0·001 (two sided test that the difference between the number of deaths observed and that expected could have occurred by chance).

Table 6 Trends in mortality at ages less than 85 years by cumulative radon exposure, estimated cumulative arsenic exposure, and duration of employment

	*Cumulative radon exposure**			*Estimated cumulative arsenic exposure**		*Duration of employment†*		
Cause of death	*No‡*	*p Value§*	*Direction of trend*	*p Value§*	*Direction of trend*	*No*	*p Value§*	*Direction of trend*
Tuberculosis	16	NS ‖	+	NS	+	11	NS	+
Lung cancer	667	<0·001	+	<0·001	+	503	<0·001	+
All cancers except lung	278	NS	−	NS	+	244	NS	−
Mental disorders	14	NS	−	NS	+	14	0·03	−
Rheumatic fever and rheumatic heart disease	13	NS	−	NS	−	10	NS	−
Other circulatory diseases	750	NS	−	0·015	−	659	NS	−
Pneumonia	44	NS	+	NS	−	40	NS	+
Other respiratory diseases	89	NS	+	0·012	−	78	NS	−
Cirrhosis of liver	60	NS	+	NS	−	53	NS	+
Other digestive diseases	34	NS	+	NS	−	28	NS	+
Urinary diseases	23	NS	−	NS	+	17	NS	+
Suicide	49	0·035	−	NS	−	35	NS	−
Homicide	7	NS	+	NS	+	5	NS	−
Accidents	109	NS	+	NS	−	82	NS	−
Other known causes	58	NS	+	NS	+	51	NS	+
All known causes except malignant neoplasms, accidents, and violence	1101	NS	−	0·008	−	961	NS	−
All causes	2246	0·002	+	0·07	+	1860	<0·001	+

*Lagged by five years, and excluding deaths and person-years in first 10 years after start of employment.
†Considering only deaths and person years 15+ years after start of employment among those employed less than 15 years.
‡Number of deaths included in trend tests for arsenic and radon.
§Two sided test of hypothesis that there is no trend in mortality.
‖ NS = non-significant ($p > 0·05$).

10 year lag period. In analyses restricted to exposures during the last 10 years, only lung cancer was significantly associated.

Estimated cumulative arsenic exposure lagged by five years was also significantly positively related to all cause and to lung cancer mortality (table 6), but was not significantly positively related to any other cause. Only the risk of lung cancer remained significantly positive in analyses with no lag period or a 10 year lag period, and with consideration only of exposures during the past 10 years. There were significant negative relations of estimated arsenic exposure to risks of circulatory diseases and respiratory diseases other than pneumonia, in analyses with a five year lag (table 6), or 10 year lag, and for respiratory diseases with no lag period, but not otherwise.

Duration of uranium mining (table 6) was significantly positively related to risks of mortality from all causes and lung cancer, and significantly negatively related to risk of mortality from mental disorders.

Discussion

The West Bohemian uranium miner cohort is one of the main sources of information on the health effects of an atmosphere with a high radon concentration. Several papers have analysed data on lung cancers in the cohort,[6–8] and we have recently reported on other cancer risks.[9] Data from several other uranium miner cohorts have shown raised risks of various non-malignant causes,[10 11 15] although with little examination of the relation to factors such as age at mining exposure and exposure levels. Mortality from non-malignant causes has virtually not been analysed in the West Bohemian cohort, however; nor have the completeness of follow up and its impact on the West Bohemian findings been examined.

Czechoslovakia does not have a well established system for routine follow up of epidemiological cohorts. Previous publications on the Czechoslovak uranium miners have relied on the Ministry of Interior population registry files to determine vital status since 1975. We were suspicious, however, that this method was incomplete. The further checks we conducted on men apparently alive in the Ministry's files, substantially altered the findings for recent follow up: a further 210 deaths and 33 emigrations were found, and the all cause SMRs for 1981–85 and 1986–90 rose from 111 and 86 respectively before these checks, to 138 and 139 after them. The newly found deaths were not biased by cause compared with those already known from the Ministry of Interior follow up, implying that if there are any deaths still missing among the 32 miners still only located via the Ministry of Interior files, they are unlikely to be biased by cause. There were 41 deaths in the study with cause unknown, mainly because the place of death within Czechoslovakia was unknown and therefore the death certificate could not be located. There is no obvious reason why these should have been biased by cause, but they imply that the true cause specific SMRs, if cause were known for all deaths, would be about 3% greater than those shown.

Uranium miners were entitled to lifelong medical care in Uranium Institute hospitals. This care was better than that available to the general population, and therefore was deliberately used by the men, but it was available only in mining areas and not if miners moved away. There may therefore be some diagnostic bias in ascertainment of cause of death in the miners compared with that in the population as a whole, which is likely to have diminished in more recent years as miners left the mining areas. It seems unlikely, however, that such diagnostic bias could explain any of the excesses for non-cancer mortality found in the miners in the present analyses, or account for more than a small fraction of the lung cancer

excess. In the early years of follow up, the relative risk of death compared with that in the general population will have been affected by the healthy worker effect,[24] but this effect will have diminished over time, and for the overall follow up it will have been of modest effect.

The raised risk of mortality from tuberculosis was only present in miners more than 20 years after entry to the mines, and many years after most of the mines had closed. One possibility is that this was a late result of primary infection in the mines. Increased transmission of tuberculosis while working in confined spaces underground would be unsurprising, and raised risk of tuberculosis has been described in two previous uranium miner cohorts,[10 11] (in one, data were not presented on the relation to duration since first exposure,[11] and in the other risk was slightly greater in the first 10 years after first exposure than subsequently).[10] It is interesting that all but one of the Czechoslovak miners with tuberculosis were born before 1930: a national BCG immunisation campaign was conducted in Czechoslovakia in 1948–9 restricted to persons born in 1930 onwards. A possible reason for the late deaths from tuberculosis might be that silicosis typically occurs many years after starting mining, and its presence could raise the risk of tuberculosis or could complicate tuberculosis leading to accelerated fatality from the infection. Although silicosis was rare in the miners and only four of the deaths involving tuberculosis were stated to be from silicotuberculosis, it is possible that others involved silicosis without this being stated on the death certificate.

The increased mortality from cirrhosis in the cohort is likely to reflect heavy drinking as part of the lifestyle of the miners, who were well paid compared with other Czech workers. The excess mortality from cirrhosis ceased at age 65, when the men will have retired from work. In Colorado uranium miners an excess mortality from alcoholism but not cirrhosis has been found.[10]

The late increase in mortality from non-malignant, non-infectious, respiratory diseases in the cohort might reflect the long term effects of dust inhalation in the mines. Decreased lung function has been shown in uranium miners in Colorado[26] and New Mexico.[27] Mortality from silicosis has been increased in several uranium miner cohorts,[10 11 15] and in New Mexico chest x ray film abnormalities compatible with silicosis were found in 9% of miners examined.[27] In the Czechoslovak miners, however, only 10 death certificates mentioned silicosis or silicotuberculosis, and the mortality from non-malignant, non-infectious, respiratory diseases was mainly from chronic bronchitis and emphysema (59 cases). In the Colorado miners,[10] and to a lesser extent those in Newfoundland[13] and New Mexico,[16] but not appreciably in Ontario,[11] there seems to have been a raised risk of non-infective, non-malignant respiratory diseases other than silicosis.

Mortality from cardiovascular disease is increased in miners exposed to radon in Sweden,[14] but not in Canada[11 13] or Cornwall,[12] and not overall in Colorado.[10] Comparison of the present data with these studies is unsatisfactory, however, because they lack data on risks by time since entry to risk: one would expect low risks soon after entry, because of the healthy worker selection effect, even if mining causes an eventual raised risk. In Colorado uranium miners an excess risk of cardiovascular deaths due to rheumatic fever was found,[10] but risk from this cause was not increased in our data. Excess mortality coded to cardiovascular disease might occur if pulmonary heart failure occurred from dust related respiratory disease. Only 26 of the 779 non-rheumatic circulatory deaths, however, were coded to pulmonary heart failure (ICD-8 426; ICD-9 415-7). There is insufficient information on the smoking and diet of the miners to know if these explain their cardiovascular mortality.

Waxweiler *et al* [10] found that mortality from chronic nephritis and renal sclerosis was increased in Colorado uranium miners. The lack of increased mortality from urinary disease in the present cohort argues against an effect of uranium exposure.

Raised mortality from accidents and violence has been found in all cohorts of uranium miners in which the risk has been examined,[10 11 15 16] and the Czechoslovak miners were no exception. Most of these deaths in the Czechoslovak miners were from accidents, but much the greatest relative risks were for homicide. Mortality from homicide was not increased in Colorado[10] or New Mexico[16] uranium miners. The raised mortality from accidents continued for many years after the men had left the uranium mines (although they may still have been employed in hazardous occupations), but decreased steeply with attained age—a decrease noted also in the only other study to examine this.[10]

The arsenic analyses should be interpreted cautiously, as they are based on indirect and approximate exposure estimates. They showed an association with risk of lung cancer, however, which accords with much previous evidence of an aetiological relation.[28 29] The other significant associations with exposure to arsenic, by contrast, were inverse, not entirely consistent, and most unlikely to be aetiological.

The relation of radon exposure to lung cancer in the West Bohemian miners was highly significant and the aetiological nature of the relation is clear from studies of miners and animal experiments.[30] Other cancers overall showed no increased risk or relation to radon. Site specific cancer risks in this cohort are discussed elsewhere.[8 9] The only other significant relation to radon exposure, for suicide, was negative and implausibly aetiological.

In summary, the miners showed a sizeable increase in lung cancer risk due to radon exposure, and in Jáchymov possibly due also to arsenic exposure. Accidents and violence, and chronic respiratory disease risks were increased, although risks of silicosis in the West Bohemian miners seem to be less than

in several other uranium mines; alcohol related mortality was increased; and mortality from cardiovascular disease was increased, but it was unclear, and needs further investigation, whether or not this was of occupational origin.

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