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Exposure–Response of Silicosis Mortality in Swedish Iron Ore Miners

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Objectives: To assess the exposure–response relationship between exposure to quartz and fatal silicosis.

Methods: The mortality from silicosis in 7729 miners was analyzed and compared to their estimated exposure to respirable quartz. The miners had been working as a miner for at least 1 year between 1923 and 1996. Their mortality between 1952 and 2001 was studied by using information from the national cause of death register. Both underlying and contributing causes of death were considered in the analysis. The exposure to quartz was estimated from job titles and using 3239 measurements of personal exposure to respirable quartz from 1965 to 1999. The mortality rates were adjusted to attained age and years of birth using a Poisson regression.

Results: The median cumulative exposure among the 7729 miners was 0.9 mg × years m^{-3}. There were 58 deaths from silicosis. Their median cumulative exposure was 4.8 mg × years m^{-3}. The crude mortality rate was 53 cases per 100 000 person-years with an exposure–response relationship.

Conclusion: There seems to be an increased risk of fatal silicosis at exposure levels around 3 mg × years m^{-3} for respirable quartz.

Keywords: epidemiology; fibrosis; mining; occupation; quartz

INTRODUCTION

Exposure to quartz still poses a risk for silicosis in mining, construction and foundries in many countries (Ross and Murray, 2004). Many countries have occupational exposure levels to protect workers from developing severe silicosis. There is likely to be a threshold level of exposure to quartz as the risk for silicosis only occurs in groups with considerable exposure. However, there is still uncertainty about the risk for long-term exposure to respirable quartz at moderate levels. Some studies indicate that control of long-term exposure to 0.1 mg m^{-3} of respirable quartz, the current exposure limit value in many countries, does not protect from silicosis morbidity (Greaves, 2000; Chen *et al.*, 2001; Sherson, 2002; Churchyard *et al.*, 2004; Steenland, 2005) or mortality (Sherson, 2002; ‘t Mannetje *et al.*, 2002; Steenland, 2005). Silicosis can be of variable severity. It can not only occur with minor impairment of respiratory function but also cause death. There is limited data on the dose–response relationship for severe silicosis. An analysis of silicosis mortality including 170 deaths among workers in different industries as underground miners, diatomaceous earth workers, granite workers and sand workers showed that long-time exposure to 0.1 mg m^{-3} of respirable quartz meant a risk of death from silicosis (‘t Mannetje *et al.*, 2002).

In this study, we assessed the exposure–response relationship between exposure to respirable quartz and silicosis mortality in iron ore miners with the focus to understand the risk of long-term exposure to levels at around 0.1 mg m^{-3}.

MATERIALS AND METHODS

This is a follow-up mortality study of male miners, who had worked as a miner for at least 1 year between 1923 and 1996. The miners were identified from the company’s personnel records, which includes

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each miner's employment time, occupation and place of work in the mine. Causes and dates of death were collected from the national cause of death register. Only deaths between 1952, when the Swedish causes of death register started, and 2001 were considered in the analysis. Using the national population register, we were able to find out if the workers were currently living in Sweden. The Swedish individual registration number makes it possible to find current or latest address of the miners, or whether they have emigrated. Individuals not found there or in the death register were excluded from the cohort. The inclusion criteria were fulfilled by 7729 male miners. Women were by law forbidden to work underground in Swedish mines before the 1970s and were excluded from the analysis.

Causes of death

Different International Classifications of Diseases (ICD6–ICD10) were used during the follow-up. In the analysis, both underlying and contributing deaths in silicosis were used (ICD6 and ICD7 523.0, 523.1; ICD8 515.0, 515.1; ICD9 502; ICD10 J62.8).

Exposure

The iron ore mines in northern Sweden are the biggest underground iron ore mines in the world. They have been in operation for >100 years. All mining has been underground in Malmberget since 1923. The mine in Kiruna started going underground in the mid-1950s and from 1965 all mining has been underground.

Wet drilling was introduced during the 1930s. In the 1950s, wetting of blasted rock started. The underground mines were ventilated mainly by self-draught and compressed air until the 1960s. When diesel-powered mining equipment was introduced in the 1960s, it required installation of mechanical ventilation. Since the beginning of the 1980s, there has been an increased use of tight, ventilated cabins with filtering of supply air in vehicles in the mines. Remote-controlled drilling has been introduced in some parts of the mines during the last 10 years.

During the years, the work has become less physically demanding, and the working time per week has been shortened, from 48 h in the 1940s to 35 h in the 1990s.

The company has measured the exposure to respirable dust and quartz by gravimetric methods since 1965. The measurements were performed by personal sampling using routine methods, i.e. cyclones with a 5-μm cut-off point. The sampling was mainly performed during 4 h of a work shift. The content of quartz (SiO_2) in the samples was estimated by X-ray diffraction. The total number of available measurements of respirable dust samples was 3239. The mean of quartz content was 2.5% with a range of 2.0–3.0% ($n = 3122$). In samples which had not been analyzed for quartz, the concentration was estimated by assuming that 2.5% of the dust was quartz.

The sampling protocols contained information about job titles. Job titles were combined with exposure data over time to create a job exposure matrix (JEM) by safety engineers from the mines and an occupational hygienist (KE). In the JEM, similar exposure levels were estimated before 1965 as during 1965–1973. Thus, for the entire period before 1965, we used the time-average level for 1965–1973 in those jobs for the analysis.

Analysis

The cumulative exposure (mg $\times$ years m^{-3}) was estimated by multiplying the estimated concentration with the number of years in that exposure level. For each subject, the number of person-years was defined as the number of years from the first employment in the mine until the death or end of the study. These and deaths from silicosis were derived for each category of cumulative exposure. The crude rates were also adjusted by a Poisson regression model using attained age and year of birth. To estimate a possible underestimation of previous exposure, we also made an analysis in which we assumed that the exposure levels were five times higher before 1940.

For the analyses, the software S-PLUS was used.

Ethics

The Ethics Committee of the University of Umeå approved the study (03-040).

RESULTS

Jobs with the highest time-average respirable quartz exposures were drillers, loaders, shotcreters (applier of concrete to the rock ceiling and walls) and chute gate operators (drawing crude ore out off the magazine at shrinkage stoping) (Table 1). The mean exposure to respirable quartz between 1968 and 1973 for truck drivers, haulage workers and repairmen was estimated to be 0.07, 0.05 and 0.05 mg m^{-3}, respectively. The mean exposure for all these jobs between 1974 and 1999 was estimated to be 0.0 1 mg m^{-3}. The mean exposure during 1974 and 1995 for air, water and ventilation operators was estimated to be 0.03 mg m^{-3}; for construction

Table 1. Exposure to respirable quartz in the mines expressed as time average during 1910–1973 and 1974–1999 among drillers, loaders, chute gaters and shotcreters, respectively

Period	Drillers (mg m^{-3})	Loaders (mg m^{-3})	Chute gaters (mg m^{-3})	Shotcreters (mg m^{-3})
1910–1973	0.21	0.35	0.19	1.00
1974–1999	0.02	0.02	0.02	0.06

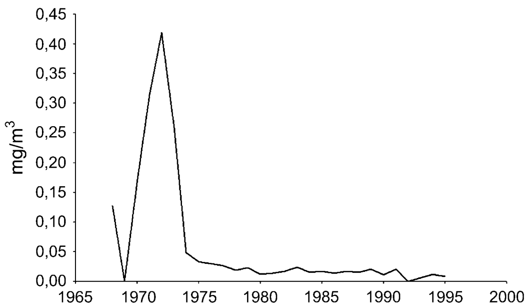

Fig. 1. Mean exposure to respirable quartz (mg m^{-3}) between 1968 and 1995 based on available data from personal sampling. No measurements in 1969 and 1992.

workers, chargers, machine attendants, laboratory technicians and scalers 0.02 mg m^{-3}; and for truck drivers, supervisors and for greasers 0.01 mg m^{-3}.

The exposure levels of respirable quartz based on available data from the personal sampling between 1968 and 1995 are shown in Fig. 1. During 1968 and 1973, the exposure was relatively high, with annual average respirable quartz exposure between 0.1 and 0.4 mg m^{-3}. Measures to reduce the exposure were implemented during these years and as a result of this the exposure levels from 1974 onward were much reduced compared to the previous years.

There were 58 deaths from silicosis including both underlying and contributing cause of death. They were on average 77 years of age at death and their median cumulative exposure was 4.8 mg × years m^{-3} (Table 2). In 22 of the deaths, silicosis was registered as underlying cause of death. Lung tuberculosis and lung cancer were mentioned in one and seven of the 58 death certificates, respectively. No miner had unspecified pneumoconiosis reported on their death certificates.

From the personnel files in the mines, we studied if men in the two lowest exposure categories (cumulative exposure <3 mg × years m^{-3}; n = 13) had previous exposure to respirable quartz prior to employment in the studied mines. Data were found for nine men. They had worked in other mines and in hydroelectric construction for on average 5.8 years (range 2.1–9.9).

The average crude mortality rate for silicosis was 53.2 per 100 000 person-years increasing from 11.0 in the lowest exposure category (0–0.9 mg × years m^{-3}) to 214 in the highest (>7 mg × years m^{-3}) (Table 3 and Fig. 2, line A). After adjusting for attained age and year of birth, the dose–response curve was somewhat reduced for the higher cumulative exposures (3–6.9 mg × year m^{-3}) compared to the unadjusted exposure–response curve (Fig. 2, line B). An adjusted analysis assuming five times higher exposure levels before 1940 showed lower risks in the exposure groups of 3–4.9 and 5–6.9 mg × years m^{-3} but higher for >7 mg × years m$-^{3}$ (Fig. 2, line C). Data based on only underlying causes of death is also presented in Table 3.

Table 2. Characteristics for the cohort

	First quartile	Median	Third quartile
All miners (n = 7729) including all deaths (n = 3177)			
Year of birth	1917	1932	1945
First year of exposure	1949	1956	1969
Age at start of exposure	20	24	30
Age at end of exposure	29	41	55
Years of exposure	4.3	10	22
Year of death	1976	1985	1993
Age at death	59	69	78
Cumulative dose[a]	0.28	0.88	2.34
Deaths from silicosis (n = 58)			
Year of birth	1894	1905	1912
First year of exposure	1924	1929	1939
Age at start of exposure	24	30	34
Age at end of exposure	52	58	62
Years of exposure	17	25	33
Year of death	1973	1981	1991
Age at death	70	78	85
Years from first exposure to death	42	49	54
Years from last exposure to death	15	22	27
Cumulative dose[a]	3.3	4.8	6.4

[a]Respirable quartz, mg × year m^{-3}.

An analysis comparing risks according to year of birth showed that the oldest group had a higher risk. The relative risk for those born in 1910–1919 was 0.50 [95% confidence interval (CI) 0.27–0.94] using those born before 1909 as a reference group. The corresponding relative risk for those born in 1920 and later was 0.17 (0.049–0.57). When assuming a five times higher exposure level before 1940, the relative risks for those born 1910–1919 were 0.67 (95% CI 0.36–1.28) and 0.30 (0.08–1.1) for those born ≥1920 or later.

DISCUSSION

Silicosis is a disease with variable severity. Studies including mild silicosis will show higher risks than studies of fatal or very severe silicosis. Our risk estimates can be too high if the analysis has included deaths misclassified as silicosis, but too low if cases with silicosis have been undiagnosed or not reported on the death certificates. A few American studies have found both over- and under-diagnosis of silicosis (Cottrell *et al.*, 1992; Goodwin *et al.*, 2003; Rosenman *et al.*, 2003). Silicosis may be misclassified as other lung diseases, e.g. chronic obstructive pulmonary disease, tuberculosis, lung cancer or

Table 3. Number of deaths from silicosis and mortality rates by cumulative dose based on underlying and contributing causes of death [corresponding data from underlying causes of death]

Cumulative dose	Corresponding exposure level for 45 years	No. of deaths from silicosis	Person-years	Mortality rate crude	Rate ratio adjusted[a]	Mortality rate adjusted[a]
0–0.9[b] (0.4)[c]	0–0.02[d]	4 [0]	41159	9.71 [0]	0.16 (0.055–0.48)[e] [na]	18.7 [na]
1–2.9 (1.8)	0.02–0.07	9 [6]	36527	24.6 [15.1]	0.28 (0.13–0.61) [0.51, 0.17–1.5]	32.8 [19.8]
3–4.9 (3.9)	0.07–0.11	20 [7]	17033	117 [38.8]	1 (ref) [1 (ref)]	117 [38.8]
5–6.9 (5.9)	0.11–0.16	15 [5]	9750	154 [48.7]	1.1 (0.55–2.1) [1.03, 0.32–3.2]	129 [40.0]
>7 (8.3)	>0.16	10 [4]	4456	224 [85.6]	1.2 (0.57–2.6) [1.4, 0.42–4.9]	140 [46.6]
Total	na	58 [22]	108925	53.2 [20.2]	na	na

na, not applicable; ref, reference group.
[a]Poisson regression with adjustments to year of birth and attained age.
[b]mg × years m^{-3}.
[c]Mean value of category.
[d]mg m^{-3}.
[e]95% CI.

cardiovascular diseases (Goodwin *et al.*, 2003). The cases have mostly died a long time after they stopped working as a miner and a differential misclassification according to exposure seems improbable as the doctors would have rarely been aware of their cumulative exposure. We think that it is more probable that our estimates are based on too few cases of silicosis in the cohort rather than over-diagnosis as a case probably have been carefully examined before death, while signs of silicosis may have been disregarded in persons with other severe diseases.

Our risk estimates are too high if we have underestimated the exposure. There are two major possibilities. We have underestimated the exposure especially in earlier years, when there were no measurements, or the workers had been exposed to quartz in other jobs before or after they worked in the mine. The strength of our exposure assessment is that it is based on measurements including analyses of respirable quartz. However, we had no gravimetric exposure measurements before 1965. A possible cause of the lower risk for people born after 1910 is that we have underestimated the exposure to those born before 1909. A higher risk of tuberculosis in earlier years may have contributed to a higher susceptibility, but only one of the deaths from silicosis had tuberculosis recorded on the death certificate. An analysis based on a five times higher exposure before 1940 showed at a cumulative exposure >7 mg × years m^{-3} a higher risk than when we assumed similar exposure before and after 1940 (Fig. 2, lines B and C). The risk can go either way depending on where the cases and person-years move. The same analysis also found lower risks in groups exposed to 3–6.9 mg × years m^{-3} but still a risk in workers exposed to <3 mg × years m^{-3} (Fig. 2, lines B and C). Some subjects may have been exposed to quartz in other environments than the mines we have studied. We have checked this in the two lowest exposure categories. We found some

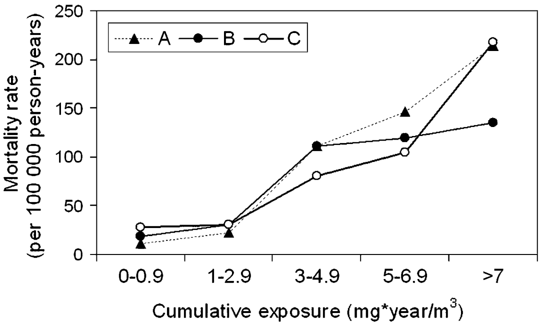

Fig. 2. Mortality rate of silicosis (per 100 000 person-years) according to cumulative dose of respirable quartz (mg × year m^{-3}). (A) Crude mortality rates using the original cumulative exposure estimates with no adjustment to possible confounders. (B) Adjusted mortality rates according to a Poisson regression model using the original cumulative exposure estimates as a categorical variable with adjustment to attained age and years of birth. (C) Adjusted mortality rates using a five times higher exposure before 1940, else similar to model B.

such cases, but we could not estimate the level. Thirteen of 58 deaths, i.e. 22%, occurred in workers exposed to doses below 3 mg × years m^{-3}. We doubt that all these 13 deaths have been misclassified due to too low-exposure estimates. Thus, we cannot exclude a risk in workers with such low exposure. Furthermore, no author has identified any exposure level free of risk (Greaves, 2000; Steenland, 2005). However, the material is too small and the exposure estimates too uncertain to make a detailed analysis of risks at low exposure.

Thus, a possible under-diagnosis of silicosis will underestimate the risk, but a possible underestimation of exposure will overestimate the risk. We do not have data to estimate the size or direction of the total bias.

Steenland has recently published a review on exposure–response data and risks of different outcomes following quartz exposure (Steenland, 2005). There are only a few exposure–response studies of silicosis morbidity with follow-up after end of employment (Hnizdo and Sluis-Cremer, 1993; Steenland and Brown, 1995; Chen *et al.*, 2001; Churchyard *et al.*, 2004) and still fewer of silicosis mortality (‘t Mannetje *et al.*, 2002). Morbidity studies show a lifetime risk at 4.5 mg $\times$ years m^{-3} of respirable quartz of 470/1000 to 770/1000 (sic) (Steenland, 2005). The study by ‘t Mannetje et al. found, based on only underlying causes of death, a risk of fatal silicosis before 75 years of age of 19/1000 (‘t Mannetje *et al.*, 2002; Steenland, 2005). They studied six pooled cohorts of underground miners, diatomaceous earth workers, granite workers and sand workers from four countries in three continents, which may result in heterogeneity in estimations of exposure and in diagnosing cause of death. Their study also had difficulties in estimating historical exposure, as they needed to convert particle measurements to mg m^{-3} of respirable quartz, while almost all our measurements are directly based on gravimetric measurements of respirable quartz. For only underlying causes of death, we have found a crude mortality rate of 20/100 000 person-years compared to 28.8/100 000 person-years reported by ‘t Mannetje *et al.* (2002).

The current occupational standard for respirable quartz in Sweden and many other countries is 0.1 mg m^{-3}. Our study adds to other dose–response studies showing that exposure to this level over a working life of $\sim$45 years is insufficient in protecting workers from silicosis (Greaves, 2000; Chen *et al.*, 2001; Sherson, 2002; ‘t Mannetje *et al.*, 2002; Churchyard *et al.*, 2004; Steenland, 2005). In our study, there seems to be a risk also in groups exposed to lower levels. There is no consensus how low an acceptable risk level ought to be. Even levels of as low as 0.05 or 0.01 mg m^{-3} have been reported to be associated with an increased risk (Greaves, 2000; Sherson, 2002; Steenland, 2005).

CONCLUSION

We conclude that our study showed that cumulative respirable quartz exposure of $\sim$3 mg $\times$ years m^{-3} or more is associated with an increased risk of fatal silicosis. This indicates that permissible exposure limits around 0.05–0.1 mg m^{-3} of respirable quartz is too high to protect the worker from severe silicosis if working at those levels for a full working life of $\sim$45 years.

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