AMERICAN JOURNAL OF INDUSTRIAL MEDICINE 30:529–539 (1996)

Risk of Silicosis in a Colorado Mining Community

Kathleen Kreiss, MD, and Boguang Zhen, PhD

We investigated exposure–response relations for silicosis among 134 men over age 40 who had been identified in a previous community-based random sample study in a mining town. Thirty-two percent of the 100 dust-exposed subjects had radiologic profusions of small opacities of 1/0 or greater at a mean time since first silica exposure of 36.1 years. Of miners with cumulative silica exposures of 2 mg/m^3-years or less, 20% had silicosis; of miners accumulating >2 mg/m^3-years, 63% had silicosis. Average silica exposure was also strongly associated with silicosis prevalence rates, with 13% silicotics among those with average exposure of 0.025–0.05 mg/m^3, 34% among those with exposures of >0.05–0.1 mg/m^3, and 75% among those with average exposures >0.1 mg/m^3. Logistic regression models demonstrated that time since last silica exposure and either cumulative silica exposure or a combination of average silica exposure and duration of exposure predicted silicosis risk. Exposure–response relations were substantially higher using measured silica exposures than using estimated silica exposures based on measured dust exposures assuming a constant silica proportion of dust, consistent with less exposure misclassification. The risk of silicosis found in this study is higher than has been found in workforce studies having no follow-up of those leaving the mining industry and in studies without job title–specific silica measurements, but comparable to several recent studies of dust exposure–response relationships which suggest that a permissible exposure limit of 0.1 mg/m^3 for silica does not protect against radiologic silicosis. © *1996 Wiley-Liss, Inc.*

KEY WORDS: ***silicosis, silica, dose–response, occupational epidemiology, mining health effects***

INTRODUCTION

Controversy continues about the quantitative relationship between respirable silica exposure and silicosis. Dust control in several silica industries has lowered silicosis rates [Graham et al., 1991; Hnizdo and Sluis-Cremer, 1993]. However, the quantitative basis of the present standards for silica exposure was derived almost entirely from dust measurements using impinger methods. Gravimetric methods of respirable dust measurement were introduced to common industrial usage in the 1970s, and the conversion of impinger or konimeter measurements to gravimetric equivalents in both standard setting and historical dose reconstruction is problematic. Recent evidence suggests that such conversion may require industry-specific data [Verma et al., 1989], which are rarely available.

In addition to the difficulties posed by exposure assessment, estimation of exposure–response relations is influenced by study design and silicosis assessment. The studies used for standard setting have identified silicosis cases in cross-sectional radiologic surveys of workforces [Thériault et al., 1974a,b]. Systematic data on development of silicosis after leaving employment or after long latency are not usually available in such studies.

We had a unique opportunity to evaluate silicosis

Occupational and Environmental Medicine Division, Department of Medicine, National Jewish Center for Immunology and Respiratory Medicine, and Department of Preventive Medicine and Biometrics, University of Colorado School of Medicine, Denver.
Address reprint requests to Dr. Kreiss, Division of Respiratory Disease Studies, National Institute for Occupational Safety and Health, 1095 Willowdale Rd, MS 234, Morgantown WV 26505-2845.

Accepted for publication August 30, 1995.

among residents of a hardrock mining town, many of whom had left mining employment and some of whom had never worked in mining. The latter group served as an internal comparison group to assess potential overdiagnosis of radiologic silicosis. The major employer was a molybdenum mine, and small companies had previously operated lead, zinc, and gold mines in the area. Our community population–based design allowed us to evaluate the relationships of cumulative dust and silica exposures to silicosis, without the constraints of employment status and age found in cross-sectional workplace studies.

The major mining company supplied historical respirable dust and silica measurements by job title, location, and year from 1941 through 1982, shortly before underground mining operations ceased. Midget impingers were used to collect 447 respirable dust samples from 1941 through 1976, and gravimetric measurements began in 1974. Dust samples from the 1940s were sparse, collected in uncertain circumstances, and were higher than samples collected later (Fig. 1). The opening of new mining levels in 1954, 1965, and 1972, which were worked concurrently, was likely accompanied by improvement in mine ventilation in comparison to the older level worked from the 1930s until 1974. However, no secular trend was evident for impinger data by job category or mining level. No correlation existed between average midget impinger and gravimetric dust measurements for the 32 job titles for which data were available using both methods, albeit in different time periods ($r = -0.06$). No side-by-side comparison measurements existed using midget impinger and gravimetric methods. Accordingly, we used the 649 gravimetric dust and 484 silica measurements taken from 1974 through 1982 for estimating historical job-specific exposures.

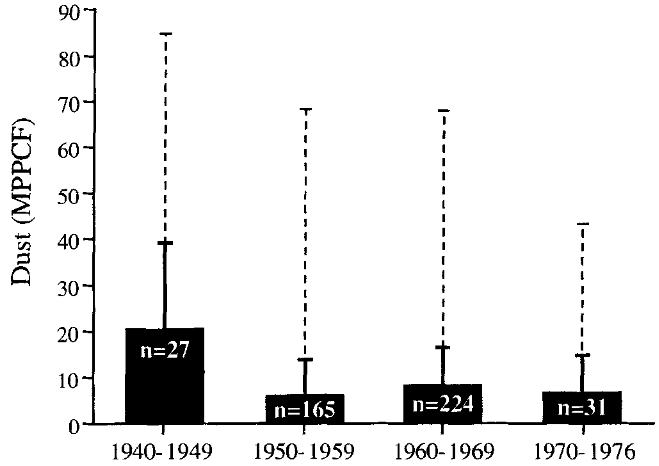

FIGURE 1. Mean midget impinger dust measurements by decade for the Leadville molybdenum mine, with standard deviation (unbroken line) and highest recorded value (dashed line) expressed in million particles per cubic foot (MPPCF).

METHODS

Subjects

We invited 149 male Leadville residents, aged 40 years or more, to participate in 1986 after they had been studied in a community-based random sample survey of respiratory disease 3 years earlier [Kreiss et al., 1989]. Of the original participants in 1983, 31 men had moved away and four had died. Outmigrants no longer available for study did not differ significantly from 1986 participants in shortness of breath, FEV_1 and FVC percent predicted, years of mining, or dust exposures. Of those invited, 134 (89.9%) participated. This population-based sample included subjects with silicosis, dust-exposed but nonsilicotic subjects, and community residents with no occupational history of silica dust exposure. We chose the 40 year age criterion because we did not expect to find silicosis among younger men.

After obtaining written informed consent, a trained interviewer completed a standardized respiratory questionnaire [Ferris, 1978] for each participant, supplemented by questions regarding silicosis and occupational history in mining and other dusty trades. Participants had a posteroanterior chest radiograph unless one was available that had been taken within the 2 years preceding the study.

Radiology

Three NIOSH-certified B readers independently classified chest radiographs for 124 of 134 subjects without personal identifiers and in random order. We defined silicosis cases as those subjects with a median radiologic profusion of small opacities of ≥1/0 using the 1980 International Labour Organization classification [ILO, 1980]. The remaining 10 films were classified by the first reader only, who classified one as abnormal with a profusion of 1/1; the clinical radiology report for this film documented an interstitial nodular pattern in the upper lobes consistent with silicosis. We evaluated concordance between pairs of B readers with the Kappa statistic for abnormality [Rosner, 1990] using a 1/0 profusion criterion, with values of 0.70 ($p < 0.0001$) for the first and second readers, 0.66 ($p < 0.0001$) for the first and third readers, and 0.58 ($p < 0.0001$) for the second and third readers. The Kappa statistics for abnormality using a 1/1 criterion were 0.80, 0.75, and 0.75, respectively.

Exposure Indices

We assessed exposure–response relations for silicosis using three exposure indices. From the occupational history (which was more detailed than that available from company personnel records), we calculated years of exposure to mining dusts in underground and surface work. Using gravimetric dust exposure data, we created a cumulative dust exposure index to partially address the substantial misclassification of exposure in the mining years index due to varying intensity of dust exposure in different job titles and mine locations. Finally, using gravimetric silica exposure data, we created a cumulative silica exposure index to address misclassification of silica exposure in the cumulative dust exposure index due to varying silica content in dust samples from different job titles.

Using the occupational histories obtained in the interview, we estimated cumulative dust and silica exposure by summing the estimated exposure for each reported job title, weighted by months in that job without regard to secular trend in exposures, if any. We estimated exposures for job titles by using the 649 job title–specific gravimetric dust measurements and 484 silica measurements taken from 1974 through 1982. For job titles with five or more measurements, we used the average of those measurements (Table I). For job titles with fewer than five measurements, we used the average of all measurements for jobs in the same fivefold dustiness category. We formed the dustiness categories using the average of four independent ratings for each job title on a 0–4 scale performed by the mining company industrial hygienist, ventilation engineer, and director of health and safety, and by our staff industrial hygienist who had previously worked for the mining company. The average dustiness score had a correlation coefficient of 0.86 with the average dust measurements for the 26 job titles with five or more dust measurements, and of 0.90 with average silica measurements for the 19 jobs with five or more silica measurements. For office-type jobs, which had no personal dust measurements, we estimated exposure to be zero. We assumed similar estimated exposures for similar job titles at other mines, which accounted for 17.1% of the personyears worked in mining among the dust-exposed population. We excluded three silicotic subjects and three nonsilicotic dust-exposed subjects from analyses of cumulative dust and silica exposure because we could not estimate their past exposures in work, such as contract assaying of mineral content and highway tunnel construction. The cumulative exposure indices for silica and for respirable dust were converted to mg/m^3-years, and we calculated average exposures by dividing the cumulative exposures by years in dust-exposed jobs.

We converted the dust index to a silica estimate for comparison with analyses based on the silica index. In the Leadville molybdenum mine, the run of mine ore had a silica concentration of approximately 35%. The average silica content of 80 dosimeter samples taken from a crusher area was 19% with a standard deviation of 11%. The mean silica content for the 483 paired silica and respirable dust measurements used in our analyses was 12.3% (standard deviation 12.0, range 0.2–100%). The correlation between paired dust and silica samples was 0.68. Accordingly, we converted the dust index to a silica estimate by application of the 12.3% average silica content of dust. This converted dust index is comparable to those used in previous studies examining exposure–response relations for silicosis without the benefit of job title–specific silica measurements.

Statistical Methods

We compared demographic data among nonminers, silicotic miners, and nonsilicotic miners, and exposure indices between the last two groups. For continuous variables, we used *t* tests to compare means and Wilcoxon rank sum tests to compare distributions (ranks) when the variables were not normally distributed. For categorical variables, we compared rates using χ^2 and Fisher's exact tests. The Spearman method was applied to correlate variables. We used logistic regression to investigate silicosis among the dust-exposed as a function of age, cumulative dust or silica exposure, time since last exposure, packyears of cigarette smoking, and their interactions. We also modeled silicosis risk as a function of average dust or silica exposure, age, years of exposure, years since last exposure, packyears of smoking, and their interactions. A stepwise procedure allowed us to select significant independent variables. For continuous independent variables, we checked the assumption of linearity in the logit [Hosmer and Lemeshow, 1989]. The rate of silicosis given by an independent vector x in the logistic regression model was estimated by $[1 + \exp(-\hat{\alpha} - \hat{B}'x)]^{-1}$, where $\hat{\alpha}$ is the estimated intercept, $\hat{B}'$ is the $1 \times s$ estimated coefficient vector, and s is the number of independent variables in the model. We used PC-SAS to conduct all data analyses [SAS Institute, 1988] and chose a probability value of 0.05 as the criterion for statistical significance.

RESULTS

Subject Characteristics

The 100 miners and 34 community controls differed significantly in mean age, packyears of cigarette smoking, and percent of current smokers, but did not differ in percent of ever smokers (Table II). None of the 34 men without dust exposure had an abnormal chest radiograph. Of the 100 dust-exposed participants, 32% were classified as silicotic; of these, seven had category II profusions, two had category III profusions, and five had predominantly irregular opacities. Men with low cumulative silica exposures tended to be somewhat older, to smoke more, and to have lower durations of dust exposure than those with moderate and high cumulative exposures (Table III). All X-ray readers classified increasing proportions of X-rays as abnormal as cumulative exposure increased.

Among the dust-exposed group, the silicotic miners

TABLE I. Mean Respirable Silica and Dust Gravimetric (mg/m^3) and Impinger (Million Particles per Cubic Foot) Measurements by Grouped Dustiness Categories and Job Titles With ≥Five Gravimetric Measurements, Leadville

Dustiness categories and job titles	Gravimetric silica			Gravimetric dust			Impinger[b]		
	No.	Mean	S.D.	No.	Mean	S.D.	No.	Mean	S.D.
Mean dustiness score: >2.5–4.0	92	0.195	0.184	98	1.91	1.54	49	17.9	19.6
Loader	65	0.193	0.154	67	1.87	1.32	27	27.1	22.0
General laborer (crusher)	24	0.218	0.254	27	2.21	2.01	6	4.6	1.5
Mean dustiness score: >1.5–2.5	228	0.086	0.096	287	1.04	1.20	139	6.2	5.7
Cave miner[a]	5	0.045	0.028	5	0.51	0.09			
General laborer (mine)	102	0.104	0.118	102	1.10	1.20	40	4.3	4.6
Miner	48	0.071	0.069	55	1.01	1.09	40	5.4	3.1
First class miner	28	0.071	0.076	70	0.85	0.93	6	5.4	0.5
Small motor motorman	7	0.066	0.042	8	1.01	0.82	3	4.7	1.2
Timberman	15	0.036	0.047	15	0.40	0.42	11	3.6	1.1
Mechanic B (crusher)	5	0.110	0.062	7	1.09	0.58	12	10.0	7.3
Welder A	8	0.170	0.058	8	2.70	2.12			
Mean dustiness score: >0.5–1.5	92	0.042	0.042	177	0.47	0.39	223	6.7	7.1
Laser motor motorman				10	0.72	0.48	16	5.5	3.1
First class trackman				6	0.63	0.23	3	3.5	0.4
Second class trackman[a]				7	0.62	0.21	1	3.9	
Dozer operator	5	0.048	0.042	5	0.40	0.25			
Shovel operator	5	0.019	0.012	8	0.44	0.58			
Utility man[a]	5	0.048	0.033	5	0.25	0.10			
First class electrician	15	0.049	0.028	23	0.51	0.33	7	3.1	1.3
Helper B[a]	8	0.060	0.029	8	0.47	0.15			
Apprentice A				5	0.44	0.38	17	5.9	3.0
Apprentice D				8	0.44	0.17			
Apprentice E				15	0.22	0.10	1	43.0	
Apprentice F				10	0.71	0.20	3	3.3	0.0
Mean dustiness score: >0–0.5	72	0.026	0.027	87	0.26	0.20	34	6.9	6.3
Floor walker	7	0.015	0.008	7	0.21	0.05			
Mechanic B (open pit)	14	0.017	0.013	14	0.27	0.17			
Mechanic, trainee[a]	6	0.009	0.003	6	0.31	0.38			
Truck driver	23	0.033	0.027	28	0.19	0.11			
Total	484	0.090	0.120	649	0.91	1.14	445	7.8	9.6

[a]No study participant had this job.
[b]Two measurements excluded because of no dustiness scores for their job titles.

significantly exceeded the nonsilicotic miners in mean age, time since first dust exposure, and all exposure indices (Table IV). Smoking status and packyears of cigarette smoking did not differ between the silicotic and nonsilicotic miners. For the 17 participants reporting a physician diagnosis of silicosis prior to the study, no statistically significant correlation existed between latency to diagnosis and cumulative or average exposure indices. Silicotic and nonsilicotic miners did not differ in average or cumulative dust or silica exposure accumulated at the minor mines around Leadville.

Exposure–Response Relationship Using Mining Years Index

All dust-exposed subjects in the study were 13 or more years since first dust exposure, and 97% were 20 or more years since first exposure. Prevalence rates of silicosis among the 100 dust-exposed subjects increased by years of dust exposure, with silicotics constituting 15.4% of miners with less than 20 years of mining; 30.0% of miners with 20–29 years of mining; and 47.1% of miners with 30 or

TABLE II. Characteristics of Leadville Community Controls and Miners, Leadville 1986

Characteristic	Community controls (n = 34)	Miners (n = 100)
Age (years)[a,b]		
Mean	55.9	60.1
S.D.	12.1	10.2
Range	41–79	41–84
Packyears smoking[b]		
Mean	17.9	29.1
S.D.	31.2	34.5
Range	0–142	0–216
Current smokers (%)[a]	5.9	29.0
Ever smokers (%)	64.7	78.0
X-ray profusion categories (%)		
0/1	8.8	12.0
1/0[a]	0.0	11.0
≥1/1[a]	0.0	21.0
≥1/1, Rounded opacities[a]	0.0	18.0
Large opacities	0.0	5.0

[a]Significant difference between the two groups in means or proportions.
[b]Significant difference between the two groups in ranks.

more years of exposure. The rates of silicosis also increased with time since first exposure, with no cases among the three subjects less than 20 years from first exposure; 17.9% of subjects 20–29 years from first exposure; 30.6% of subjects 30–39 years from first exposure; and 51.6% of subjects 40 or more years from first exposure.

Exposure–Response Using Dust Exposure Indices

Prevalence rates of silicosis among the 94 dust-exposed subjects for whom we estimated cumulative and average exposure increased with increasing average dust exposure (Fig. 2). Those with average dust exposure ≤0.4 mg/m^3 (corresponding to ≤0.05 mg/m^3 silica assuming a 12.3% silica content of dust) had a silicosis rate of 10% in comparison to a rate of 22.5% for the group with >0.4–0.8 mg/m^3 and 48.6% for the group with higher average exposures (p = 0.01). Cumulative dust exposure was also significantly related to silicosis prevalence rates. Of the group with cumulative dust exposure of >0–16 mg/m^3-years (corresponding to ≤2 mg/m^3-years of silica), 15.1% had silicosis. With exposure of >16–32 mg/m^3-years, the rate of silicosis increased to 43.3%. Men with cumulative exposures >32 mg/m^3-years had a silicosis rate of 72.7%.

Logistic regression analyses showed that cumulative dust exposure and time since last exposure predicted silicosis (Model 1 in Table V). Alternatively, the average dust exposure, years of exposure, and time since last exposure predicted silicosis risk (Model 2 in Table V). Age, time since first exposure, packyears of smoking, and interaction terms were not significant predictors of the presence of silicosis.

Exposure–Response Using Silica Exposure Indices

Of the 94 dust-exposed participants, those accumulating ≤2 mg/m^3-years silica dust had a silicosis prevalence rate of 20.0%, in comparison to a rate of 62.5% for those accumulating >2 mg/m^3-years (p = 0.004) (Fig. 3). Average silica exposure was also significantly associated with silicosis rates, which were higher than those found when we classified dust-exposed participants into subgroups of comparable cumulative dust exposure (Fig. 2). The logistic regression models showed that cumulative silica exposure and time since last exposure predicted silicosis risk (Model 3 in Table V). Alternatively, silicosis risk increased with average respirable silica exposure, years of exposure, and time since last exposure (Model 4 in Table V), while the other independent variables did not significantly contribute to silicosis risk. Figure 4 demonstrates the silicosis risk associated with increasing years of exposure at different levels of average silica exposure, holding postemployment follow-up at 10 years.

At the extremes of postexposure follow-up, one silicotic subject (with a 1/2 profusion of small opacities) reported only 1 year of mining at an average silica exposure of 0.104 mg/m^3 and follow-up 56 years later. Another subject who was not silicotic had similar cumulative exposure from 2.1 years of mining at an average exposure of 0.042 mg/m^3 and follow-up 66 years later.

Using the logistic regression model for silicosis risk based on average silica exposure, we compared the risks of a typical 25 year mining career and a 45 year mining career (Fig. 5). At an average exposure of 0.05 mg/m^3, the risks of silicosis at the end of employment were 50% for miners working 45 years and 9% for miners working 25 years in the industry. At approximate retirement age following 20 years of postexposure follow-up, the 25 year miners had a 36% risk of silicosis. At the end of life with an additional 15 years of follow-up, the silicosis risk for 25 year miners at an average silica exposure of 0.05 mg/m^3 was 67%, compared to a risk of 78% for 45 year miners followed 15 years.

Comparison of Silica and Dust Risk Estimates

Using the logistic regression models, we compared risk estimates for silicosis in relation to cumulative silica and dust exposures, assuming a 12.3% silica content of respirable dust (Fig. 6). Risk estimates using the cumulative silica

TABLE III. Prevalence (%) of Radiologic Opacities of Profusion ≥1/0 by Cumulative Silica Exposure and Reader, Leadville 1986

	Cumulative silica exposure (mg/m³-years)					
	0	>0–1	>1–2	>2–3	>3	Total exposed[b]
Number of subjects[a]	34 (2)	32 (4)	38 (1)	18 (2)	6 (1)	94 (8)
Mean cumulative silica exposure	0.0	0.6	1.4	2.5	3.6	1.5
Mean years exposure	0.0	16.0	28.2	30.6	28.2	24.5
Mean age	55.9	62.2	58.9	57.7	58.2	59.7
% ever smokers	64.7	84.4	76.3	77.8	66.7	78.7
Prevalence (%)						
Reader 1	2.9	15.6	31.6	61.1	83.3	35.1
Reader 2	3.1	17.9	24.3	68.8	80.0	33.7
Reader 3	6.3	25.0	21.6	56.3	60.0	31.4
Median reading	0.0	12.5	26.3	55.6	83.3	30.9

[a]Numbers in parentheses are subjects whose X-rays were unavailable for Readers 2 and 3.
[b]No silica exposure data were available for six of 100 miners studied.

TABLE IV. Characteristics of Leadville Silicotic vs. Nonsilicotic Miners, Leadville 1986

	Silicotic miner (n = 32)			Nonsilicotic miner (n = 68)		
Characteristic	Mean	S.D.	Range	Mean	S.D.	Range
Age (years)[a]	64.3	10.7	46–83	58.2	9.4	41–84
Packyears smoking	33.7	47.3	0–216	26.9	26.5	0–116
Years in hardrock mining[a]	27.6	11.2	1–58	22.9	10.6	0.5–46
Years since first exposure[a]	41.6	12.4	20–66	33.5	11.0	13–68
Years since last exposure	10.0	13.9	0–56	7.1	11.6	0–66
Cumulative dust exposure (mg/m³-years)[a,b]	24.2	11.7	1.1–54.0	14.2	9.0	0.1–47.5
Average dust exposure (mg/m³)[a,b]	0.97	0.38	0.37–1.77	0.64	0.29	0.25–1.64
Cumulative silica exposure (mg/m³-years)[a,b]	2.03	0.96	0.10–3.88	1.24	0.80	0.01–4.70
Average silica exposure (mg/m³)[a,b]	0.08	0.03	0.04–0.16	0.06	0.02	0.03–0.16

[a]Significant difference between the two groups in means and ranks.
[b]Six subjects excluded due to lack of a cumulative dust or silica exposure estimate—three in each group.

exposure index were considerably higher than those derived from the cumulative dust index. For example, at a cumulative exposure of 2.0 mg/m^3-years and no postexposure follow-up, the two models predicted silicosis risks of 31% and 14%, respectively. At 4.0 mg/m^3-years and no postexposure follow-up, the models predicted silicosis risks of 92% and 62%, respectively. Figure 6 also shows that silicosis risk increased markedly with follow-up after employment. For example, at a cumulative silica exposure of 2.0 mg/m^3-years, the model based on the silica index predicts that silicosis risk jumps from 31% at the end of exposure to 67% with 20 years of postexposure follow-up. At higher cumulative silica exposures, such as 4.0 mg/m^3-years, silicosis risks are above 90% even with no follow-up. The additional follow-up effect is then less marked but still evident.

Comparison of Different X-Ray Criteria

To facilitate comparison with previous studies which have used an X-ray profusion of ≥1/1 rounded opacities, we have included the logistic regression models for cumulative dust and silica exposure indices using these more stringent criteria for radiologic classification of silicosis (Models 5 and 6 Table V). The rates of silicosis are lower using the ≥1/1 criterion for radiologic silicosis, particularly at intermediate cumulative silica exposures (Fig. 7). The model derived from cumulative dust, converted to silica exposure by assuming a 12.3% silica content of dust, lowers the risk estimates for radiologic silicosis to a greater degree than the change in radiologic criteria for silicosis.

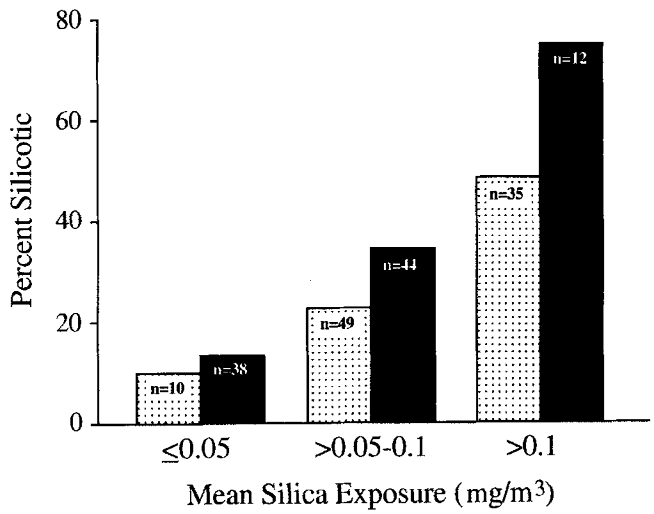

FIGURE 2. Prevalence rates of silicosis among dust-exposed subjects by average silica exposure category, Leadville 1986. Stippled bars represent rates derived from average dust exposure categories, converted to silica exposure by assuming a 12.3% silica content of dust. Solid bars represent rates based on silica measurement categories.

DISCUSSION

The most striking finding of this community-based study is the high prevalence rate of silicosis (32%) among men 40 years and older who had been exposed to hardrock mining dusts at an estimated average silica level of 0.064 mg/m^3, which is below the current permissible exposure limit. Our data support the need for following silica-exposed workers after they leave employment to assess the full burden of radiologic disease in relation to average and cumulative silica exposures.

Since nearly half of the silicotic miners were unaware of their radiologic abnormality, we concluded that their radiologic silicosis developed after they had left regular medical surveillance in mining industry employment. In longitudinal follow-up of South African gold miners, a majority of silicosis cases developed in ex-miners who had left the industry [Hnizdo and Sluis-Cremer, 1993]. Cross-sectional workforce studies never achieve the mean follow-up periods from first exposure necessary for long-latency disease; in our study, the mean time from first exposure was 36.1 years for the dust-exposed population, and 97% were 20 or more years since first exposure. The shorter time since first exposure among nonsilicotics compared to silicotics (33.5 vs. 41.6 years) suggests that additional silicosis cases may occur in the nonsilicotics with longer follow-up.

Our estimates of cumulative dust and silica exposure are subject to error, since pre-1974 exposure estimates were based on job-specific gravimetric data collected since 1974, a period which accounted for 30.4% of the personyears worked by study participants. The more recent exposure data have the advantages of greater numbers of measurements, job title–specific silica measurements, and gravimetric units, obviating assumptions regarding a conversion factor applied to midget impinger data. On the other hand, these data do not allow adjustment for possible secular changes in dust exposure due to ventilation and production changes. We suspect that historical exposures may have been higher than those used in our calculation of the cumulative dust and silica exposure indices, particularly in the 1940s, but personyears of mining in that decade account for only 5.7% of the total (and 1.6% of the major mine personyears). We were unable to confirm our suspicion of higher earlier exposures using the impinger data from the subsequent three decades (Fig. 1), even with job title–specific data. If our cumulative respirable dust and silica exposure indices underestimated exposure, models using these indices would overestimate quantitative risk of silicosis associated with the estimated exposure. It is also possible that our exposure indices overestimated exposure if, for example, measurements were taken in circumstances suspected to generate higher than average dust and silica levels.

Our study has two potential biases, in addition to possible misestimation of historical silica exposures. First, outmigration from the highest town in North America might have an effect in either direction: symptomatic ex-miners may have left for lower altitudes, resulting in an underestimation of silicosis rates; alternatively, miners without radiologic silicosis may have been able to obtain employment elsewhere while silicotics remained, resulting in an overestimate of silicosis rates. Outmigrants between 1983 and 1986, during which time the underground operations closed, provided no evidence for a bias in either direction, since they did not differ in chest complaints or spirometry from those miners who remained resident in Leadville. Second, exposure–response relations derived from this mining community at 3,100 meters may have overestimated the exposure-related risk of silicosis because of the increased minute ventilation required to compensate for altitude-associated hypoxemia. Long-term Leadville residents have been shown to have a depressed ventilatory response to hypoxia compared to lowlander sojourners at this altitude; the increases in minute ventilation for Leadville residents at 3,100 meters associated with moderate to heavy workloads requiring the same oxygen consumption at sea level among sea level residents are in the range of 14–27% [Dempsey et al., 1972]. However, the resulting increased risk for a particular exposure level among Leadville miners compared to sea level silica-exposed workers is small in comparison to other uncertainties in historical dose reconstruction in this and all published studies.

In contrast to other investigators who estimated silica exposures from the average silica content of ore or dust samples [Verma et al., 1989; Hnizdo and Sluis-Cremer, 1993; Thériault et al., 1974a; Steenland and Brown, 1995], we had the advantage of having *job title–specific silica* exposure measurements which should have resulted in less

TABLE V. Logistic Regression Models Using Two X-Ray Profusion Criteria and Alternative Dust and Silica Exposure Indices, Leadville 1986

Independent variables	Estimated coefficients	S.E.	p value	Odds ratios[a]	95% C.I. of odds ratios	Log likelihood
Profusion ≥1/0						
Model 1						−43.69
Constant	−4.0613	0.8281	0.0001			
Years since last exposure	0.0749	0.0232	0.0013	2.1	1.3–3.3	
Cumulative dust exposure (mg/m^3-years)	0.1401	0.0326	0.0001	3.1	1.9–5.3	
Model 2						−42.61
Constant	−7.3550	1.6797	0.0001			
Years since last exposure	0.0823	0.0277	0.0030	2.3	1.3–3.9	
Years of dust exposure	0.1136	0.0390	0.0035	3.1	1.5–6.7	
Average dust exposure (mg/m^3)	3.7210	0.8982	0.0001	4.5	2.2–9.3	
Model 3						−44.76
Constant	−4.0038	0.8316	0.0001			
Years since last exposure	0.0765	0.0238	0.0013	2.1	1.3–3.4	
Cumulative silica exposure (mg/m^3-years)	1.5992	0.3855	0.0001	4.9	2.3–10.5	
Model 4						−43.95
Constant	−7.1575	1.6637	0.0001			
Years since last exposure	0.0859	0.0284	0.0024	2.4	1.4–4.1	
Years of silica exposure	0.1143	0.0388	0.0032	3.1	1.5–6.7	
Average silica exposure (mg/m^3)	40.1495	10.2630	0.0001	7.4	2.7–20.4	
Profusion ≥1/1 rounded						
Model 5						−32.05
Constant	−5.0745	1.0982	0.0001			
Years since last exposure	0.0618	0.0288	0.0316	1.9	1.1–3.3	
Cumulative dust exposure (mg/m^3-years)	0.1430	0.0377	0.0002	3.2	1.8–5.8	
Model 6						−34.18
Constant	−4.5926	0.9965	0.0001			
Years since last exposure	0.0557	0.0276	0.0436	1.7	1.0–3.0	
Cumulative silica exposure (mg/m^3-years)	1.4601	0.4076	0.0003	4.3	1.9–9.6	

[a]For years since last exposure and years of exposure, the odds ratio is for an increase of 10 years. For the average and cumulative silica exposures, the odds ratios are for an increase of 0.05 mg/m^3 and 1 mg/m^3-years, respectively. The comparable odds ratios for dust exposure are calculated assuming a silica content of 12.3%.

misclassification of silica exposure. The estimates of silicosis risk using cumulative and average silica exposure were higher than those derived from cumulative and average dust exposure, for which we assumed a 12.3% silica content of dust. The logistic regression–modeled odds ratio for silicosis associated with a 2 mg/m^3-years increase in cumulative silica exposure was 24.5 in comparison to 9.8 from a comparable increase in silica exposure derived from the cumulative dust exposure model, assuming a silica content of dust of 12.3%.

Our risk estimates are markedly higher than those reported for Ontario hardrock miners [Muir et al., 1989a, b; Verma et al., 1989]. However, the mean length of follow-up from first exposure was less than 18 years in the Ontario study. The difference in risk estimates between the two studies substantiates our concern that study designs based on radiographs taken at the time miners leave an industry may underestimate risk for silicosis occurring at longer latency and among ex-miners.

In contrast, our quantitative risk estimates from the cumulative dust models using a profusion criterion of ≥1/1 are strikingly similar to those found for South African gold miners [Hnizdo and Sluis-Cremer, 1993], Hong Kong granite quarries [Ng and Chan, 1994], and South Dakota gold miners [Steenland and Brown, 1995]. Each of these groups was followed, at least in part, for radiologic changes or silicosis diagnosis after employment ended. The consistency of risk estimates from these studies is quite surprising

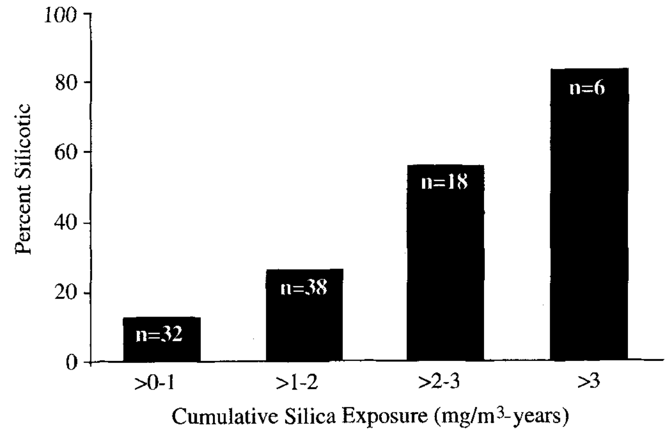

FIGURE 3. Silicosis prevalence rates by cumulative respirable silica exposure category, Leadville 1986.

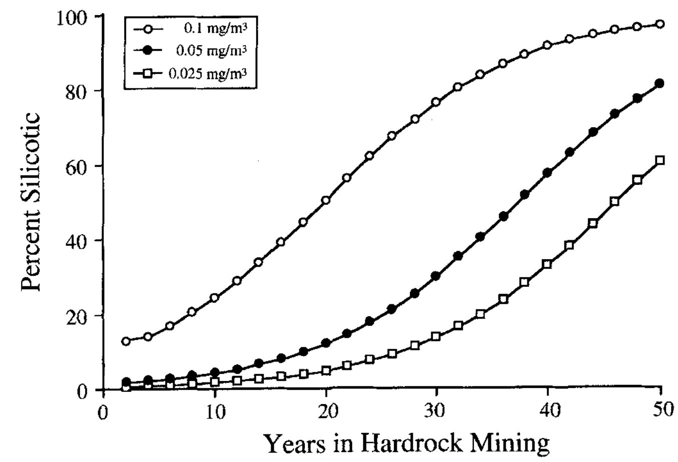

FIGURE 4. Percent silicosis by years of exposure and average silica exposures, as determined by Model 4 in Table V, with 10 years of postexposure follow-up. Average levels of silica exposure are 0.1 (open circles), 0.05 (closed circles), and 0.025 mg/m^3 (open squares).

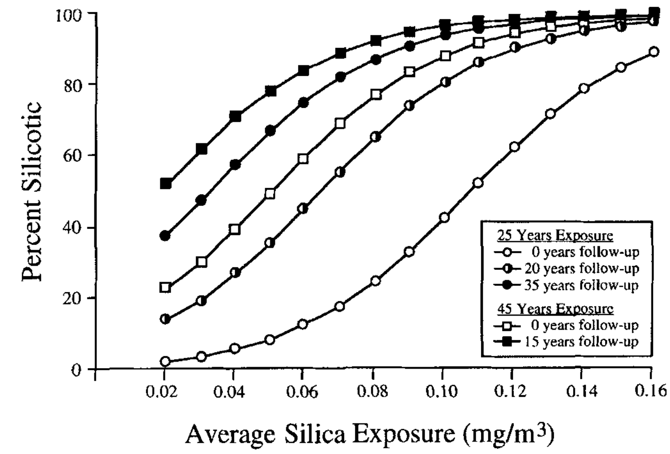

FIGURE 5. Percent silicosis by average silica exposures, as determined by Model 4 in Table V, for 25 year (circles) and 45 year (squares) mining employment, with no postemployment follow-up (open), 20 year follow-up at retirement age for 25 year miners (half open), and an additional 15 year follow-up (black) of both groups at approximate end of life.

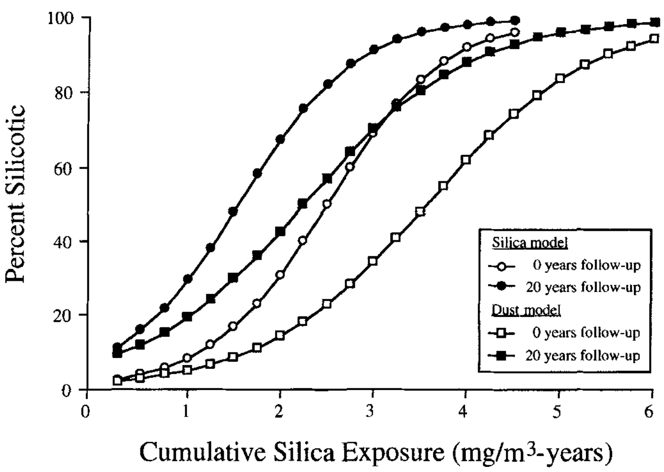

FIGURE 6. Percent silicosis by cumulative respirable silica exposure, as determined by Models 1 and 3 in Table V, for no postemployment follow-up (open) and 20 years (closed) postemployment follow-up. Circles represent cumulative silica exposure estimates based on silica measurements. Squares represent silica exposure estimates based on cumulative dust models assuming a 12.3% silica content of dust.

since study designs included longitudinal cohort follow-up, cross-sectional radiologic surveys of current and ex-workers, and death certificate ascertainment of cases. For example, the South Africa study [Hnizdo and Sluis-Cremer, 1993] showed a cumulative silicosis risk of 77% for 4.5 mg/m^3-years estimated silica exposure; in comparison, the Leadville data showed a prevalence of 68–80% for the same estimated cumulative exposure, the range being for 10–20 years of postemployment follow-up, respectively (model 5 in Table V). Similarly, the South African study reported that miners accumulating about 2.7 mg/m^3-years of respirable silica had a 25% risk of silicosis, in comparison to our estimate of 22–34% prevalence with 10–20 years of postemployment follow-up, based on our dust model and identical 1/1 profusion criterion.

Although our risk estimates using the dust exposure estimates, mean silica content of dust, and the ≥1/1 radiologic criterion were comparable to those reported by others with at least three decades of follow-up after first exposure, our quantitative risk estimates based on the silica models were higher. For example, our silica measurement–derived model predicted the silicosis risk for miners accumulating

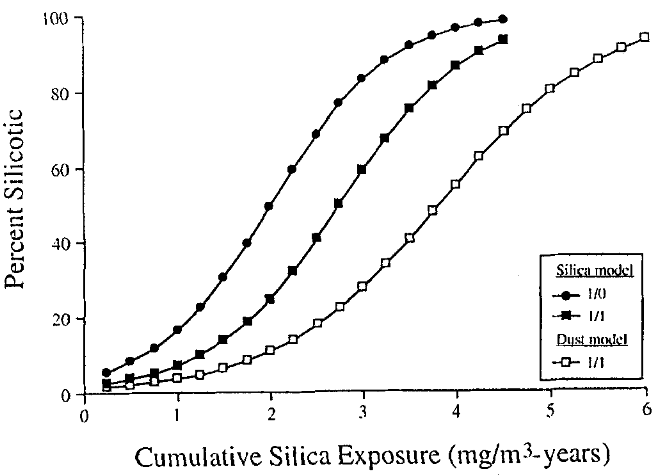

FIGURE 7. Percent silicosis after 10 years of postexposure follow-up by cumulative respirable silica exposure, as determined by Models 3 (closed circles), 5 (open squares), and 6 (closed squares) in Table V, for two different definitions of radiologic abnormality. Closed circles represent silicosis risk defined as a small opacity profusion of ≥1/0. Squares represent silicosis risk defined as a small rounded opacity profusion of ≥1/1. The closed squares represent the model based on cumulative silica exposure. The open squares represent the model based on cumulative dust exposure, converted to comparable silica exposure by assuming a 12.3% silica content of dust.

about 2.7 mg/m^3-years of respirable silica, using the ≥1/1 radiologic criterion, to be 50% with 10 years of postexposure follow-up. Thus, having job-specific silica measurements with which to model silicosis risk led to an approximate doubling of our risk estimates at modest exposures when compared to models based on respirable dust with an assumed constant silica content.

Although we have presented comparisons of our data using the ≥1/1 profusion of rounded opacities reported by others, we advise using a less conservative definition of radiologic pneumoconiosis in future studies. Our choice of a 1/0 criterion is supported by the autopsy study of South African gold miners [Hnizdo et al., 1993] which reported a sensitivity of 0.39 or less for pathologic silicosis using a 1/1 profusion criterion. A 1/0 profusion criterion improved the sensitivity, and the authors recommended a 0/1 profusion criterion for those exposed to a high average concentration of respirable silica dust. In addition to a less stringent profusion criterion, we chose to ignore categorization of predominant opacity as rounded or irregular. We had the advantage of a community control group which did not have any abnormal X-rays, suggesting that the background rate of small opacities is quite low. Smoking indices did not enter our models of risk for radiologic abnormalities, a finding similar to that of Ng and Chan who also ignored opacity shape. Finally, Ng and Chan have shown in a much larger group of silica-exposed workers that both rounded and irregular opacities are related to cumulative silica exposure, and that such classification varied considerably by X-ray reader.

Although the clinical significance of low profusion silicosis may be disputed, a public health approach to prevention is aided by early disease detection, even in a preclinical stage. Our models for silicosis risk suggest that the curve representing the 1/0 profusion criterion is shifted to the left compared to the curve representing the 1/1 radiologic criterion, as would be expected for earlier diagnosis of silicosis. Exposure–response relations using a less conservative criterion for radiologic classification of disease may be particularly useful in a disease that predisposes to clinical mycobacterial infection and appears and/or progresses after employment has ended. Additional community-based cross-sectional and prospective studies following silica-exposed workers after they leave employment would be useful to clarify exposure–response relationships using gravimetric sampling and job-specific silica measurements. Regardless of the uncertainty remaining about historical exposure estimates in this and other studies, our study documents that silicosis occurred at an unacceptably high rate among hardrock miners in Leadville, at exposures averaging below the current U.S. permissible exposure limit, and suggests that lifetime follow-up is necessary to assess the full health burden of silica dust exposures.

ACKNOWLEDGMENTS

We thank the former health and safety staff of the major mining company; our field interviewer Agnes Fabian, RN; Marilyn Kehe, who coordinated the field study and performed preliminary data analyses; and Linda Greenberg, MS, who assisted in data analyses and manuscript editing. Kyle Steenland, PhD, kindly provided comments on the manuscript. This work was supported in part by NIOSH Grant K01-OH00018 and NIEHS Grant ES00214.

REFERENCES

Dempsey JA, Forster HV, Birnbaum ML, Reddan WG, Thoden J, Grover RF, Rankin J (1972): Control of exercise hyperpnea under varying durations of exposure to moderate hypoxia. Respir Physiol 16:213–231.

Ferris BG (1978): Epidemiology standardization project. Am Rev Respir Dis 118:1–120.

Graham WGB, Ashikaga T, Hemenway D, Weaver S, O'Grady RV (1991): Radiographic abnormalities in Vermont granite workers exposed to low levels of granite dust. Chest 100:1507–1514.

Hnzido E, Murray J, Sluis-Cremer GK, Thomas RG (1993): Correlation between radiological and pathological diagnosis of silicosis: An autopsy population based study. Am J Ind Med 24:427–445.

Hnizdo E, Sluis-Cremer GK (1993): Risk of silicosis in a cohort of white South African gold miners. Am J Ind Med 24:447–457.

Hosmer DW, Lemeshow S (1989): "Applied Logistic Regression." Canada: John Wiley & Sons, Inc., pp 88–91.

International Labour Organization (1980): "Guidelines for the Use of the ILO International Classification of Radiographs of Pneumoconioses." Geneva, Switzerland: International Labour Office, Occupational Safety and Health Series No. 22 (Rev.).

Kreiss K, Greenberg LM, Kogut SJH, Lezotte DC, Irvin CG, Cherniack RM (1989): Hard-rock mining exposures affect smokers and nonsmokers differently: Results of a community prevalence study. Am Rev Respir Dis 139:1487–1493.

Muir DCF, Shannon HS, Julian JA, Verma DK, Sebestyen A, Bernholz CD (1989a): Silica exposure and silicosis among Ontario hardrock miners: I. Methodology. Am J Ind Med 16:5–11.

Muir DCF, Julian JA, Shannon HS, Verma DK, Sebestyen A, Bernholz CD (1989b): Silica exposure and silicosis among Ontario hardrock miners: III. Analysis and risk estimates. Am J Ind Med 16:29–43.

Ng TP, Chan SL (1994): Quantitative relations between silica exposure and development of radiological small opacities in granite workers. Ann Occup Hyg 38 (Supplement 1, Inhaled Particles VII, Blsevier Science Ltd.):857–863.

Rosner B (1990): "Fundamentals of Biostatistics." Boston, MA: PWS-Kent Publishing Company, pp 455–458.

SAS Institute, Inc. (1988): "SAS/Stat User's Guide, Release 6.03." Cary, NC: SAS Institute, Inc.

Steenland K, Brown D (1995): Silicosis among gold-miners: Exposure–response analyses and risk assessment. Am J Public Health, 85:1372–1377.

Thériault GP, Burgess WA, DiBerardinis LJ, Peters JM (1974a): Dust exposure in the Vermont granite sheds. Arch Environ Health 28:12–17.

Thériault GP, Peters JM, Johnson WM (1974b): Pulmonary function and roentgenographic changes in granite dust exposure. Arch Environ Health 28:23–27.

Verma DK, Sebestyen A, Julian JA, Muir DCF, Schmidt H, Bernholz CD, Shannon HS (1989): Silica exposure and silicosis among Ontario hardrock miners: II. Exposure estimates. Am J Ind Med 16:13–28.