

Safety in Mines Research Advisory Committee

Final Report

Silicosis prevalence and exposure response relationships in older black mineworkers on a South African goldmine

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Executive summary

Background

Silicosis is an incurable but preventable disease, with a number of recognised complications including tuberculosis, loss of lung function, progressive massive fibrosis and lung cancer. Recent studies have shown a high prevalence of silicosis among ex-goldminers. Although black goldminers have historically held the highest exposure jobs on the goldmines, there have remarkably been no studies of silicosis exposure response relationships in employed black South African goldminers.

Objectives

The objectives of this study were:

1. To measure the prevalence of silicosis among in-service black goldminers;
2. To measure the exposure response relationship between silica dust exposure and silicosis in this group.

Population and sample

The setting was a gold mine in the Free State. The intention was to include black mineworkers over 40 years of age to secure a longer service sample in whom enough silicosis was present to examine exposure response associations. In the final sample the youngest age was 38 years. This is also a suitable group in which to examine prevalence as the burden of silicosis falls on older workers.

Methods

A consecutive sample of 520 mineworkers returning from annual leave underwent medical examinations, including a questionnaire and chest x-ray. Among these 520 men, 85 different occupations were represented.

A cumulative exposure index was calculated for each individual by incorporating all jobs worked by that individual on the mine and an 8 hour time weighted average (TWA) respirable dust and quartz concentration assigned to each job.

TWA dust concentrations came from two different sources. Gravimetric measurements were carried out on a sample of 112 workers on the same mine (who were not part of the x-ray study) across a range of occupations. Quartz fractions were calculated by a contracted laboratory using the method of x-ray diffraction. TWA quartz concentrations were derived by applying the quartz fractions to the corresponding respirable dust concentrations.

Of the 85 different occupations in the group undergoing chest x-rays, only 26 were represented in the dust measurement study. The exposure data obtained during the project were thus augmented with exposure data from routine exposure surveys taken at the mine [Integrated Risk Management System (IRMS) database].

After entering the data from these two sources into a job exposure matrix, the 85 different

occupations were eventually reduced to 23 occupational groups by grouping together occupations with similar exposures based on the expert opinion of two occupational hygienists familiar with the mine. To each occupational group, a time weighted average (TWA) respirable dust concentration and TWA quartz concentration were assigned by taking a simple average of all concentrations available for that category.

An average intensity of exposure for each individual was calculated by dividing the cumulative exposure by the length of mining service of that individual.

Prevalence of silicosis

All 520 chest x-rays were read by two experienced readers using the International Labour Organisation Classification of Radiographs of the Pneumoconioses ("ILO"). Agreement between the two readers was very high. For example using ILO profusion 1/1 and above as the threshold for silicosis (dichotomous scale), the percent agreement was 93.5 percent and the kappa statistic 0.79, indicating excellent agreement. Most of the films were of good or acceptable quality. For simplicity of description, only the results of reader one are described further.

Out of the total of 520, only 226 chest x-rays (43.5 percent) were read as completely normal. A further 150 (28.9 percent) were read as abnormal but as having no parenchymal abnormalities on the ILO scale (i.e. were equivalent to 0/0).

Using ILO profusion $\geq 1/0$ as the definition of silicosis, the prevalence was 23.9 percent. When ILO profusion $\geq 1/1$ was used as the cut point, the prevalence of silicosis was 18.3 percent.

The first finding is thus that in among in-service black goldminers over 38 years of age, almost one in five have evidence of silicosis at the 1/1 level of profusion, and almost a quarter at the 1/0 level.

In interpreting this prevalence derived from a cross-sectional study, one has to take into account a number of factors. The group studied excluded workers under the age of 38 years, who would have a lower prevalence of silicosis in keeping with their shorter service. On the other hand, the workforce is a "healthy survivor" cohort in that workers found to have complicated pneumoconiosis (including silicotuberculosis) are required by law to be barred from further risk work and would be selected out of the workforce. The prevalence in current workers is thus an underestimate. Finally, quartz exposure carries a substantial lifelong risk of incident (newly appearing) silicosis even after exposure has ceased, so that the study underestimates the lifetime risk for any individual. In an earlier study of white South African goldminers, the onset of over half of the radiological silicosis cases occurred after the worker had left exposure.

Exposure response relationships

On the assumption that the average respirable dust and quartz concentrations have not changed on this mine over the past three decades, all of the workers in the sample were found to have worked at an average exposure to quartz below the current Occupational Exposure Level of 0.1 mg/m^3 . The high silicosis prevalence confirms the lack of protectiveness of this level against silicosis. This is in accord with the conclusion of Hnizdo and Sluis-Cremer in their earlier study of white mineworkers, and with current international recommendations, such as

those of the National Institute of Occupational Safety and Health in the USA (NIOSH).

Significant trends were found between exposure and the prevalence of silicosis for all of the exposure measures. With regard to duration of exposure, only one case of silicosis was found in the group with 15 years or less of service. However, it is difficult to interpret this duration as a threshold for the development of silicosis since there was no information on how many shorter service workers had left service because of silicosis or had developed silicosis for the first time after leaving the mine.

Among the dust exposure metrics, the strongest trend was observed for cumulative exposure to quartz, viz. a 3.2 fold increase in prevalence for every $\text{mg}\cdot\text{year}/\text{m}^3$ (across a range from 1 to 3 $\text{mg}\cdot\text{years}/\text{m}^3$). Weaker but significant trends were observed for average intensity of quartz and of respirable dust. It was not possible to determine any protective threshold for average intensity of exposure.

The most important assumption underlying the exposure response findings was that the dust concentration and quartz fraction measurements on which the cumulative exposure and average intensity variables were constructed reflect the working life exposure of the group. There is some evidence that average dust levels in the South African goldmines were unchanged between the 1940s and 1970s and possibly through the 1990s. However, data covering the period of interest need to be examined critically.

Conclusions

This is the first study of exposure response relationships for silicosis in black South African goldminers. The main findings are:

1. Almost one in five of these older, longer service black mineworkers had developed silicosis. This finding points to the urgent need for improved dust control to reduce silica exposure in this workforce.
2. Allowing for the fact that the sample in this study was chosen to represent older mineworkers, if one extrapolates these results to the goldmining industry in general, they confirm the existence of a significant epidemic of silicosis in the industry and a concomitant need for dust reduction strategies.
3. Within the narrow range of average intensity of exposure, duration of exposure is a strong determinant of the risk of silicosis. This implies that as the average contracts of service of black mineworkers lengthen, as they have been doing over the past three decades, the burden of silicosis will rise.
4. If the assumption of stability of average dust concentrations on this mine over the working life of this group of workers is correct, these workers developed silicosis despite having been exposed to an average quartz concentration below the recommended occupational exposure limit of $0.1 \text{ mg}/\text{m}^3$. This is in accord with a mounting body of evidence that an OEL of $0.1 \text{ mg}/\text{m}^3$ is not protective against silicosis.
5. The data suggest that a quartz OEL of $0.05 \text{ mg}/\text{m}^3$ would not be protective against silicosis either. However, no exposure threshold could be determined as the many sources of measurement variability and assumptions in grouping the dust data make distinctions between relatively small increments in average quartz intensity subject to error.

6. The findings support the conclusion of Hnizdo and Sluis-Cremer ten years ago, as well as the recommendation of the National Institute of Occupational Safety and Health in the USA, that a reduction of the quartz OEL from 0.1 mg/m^3 is indicated to reduce substantially the risk of silicosis. Both the earlier South African study and the current one suggest that a reduction of the quartz OEL to at least 0.05 mg/m^3 would be necessary to achieve such protection.

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Glossary

Silicosis

Fibrosis of the lung due to the inhalation of free crystalline silicon dioxide (quartz). In this report, silicosis is defined radiologically.

Prevalence

Prevalence is the proportion of people with silicosis at the time of the survey. Prevalence is entirely dependent on the group studied and is meaningless if this context is not given. For example, a sample of in service miners, which includes a large number of short service workers, will have a low prevalence of silicosis even if the lifetime prevalence is high.

Exposure metrics

Different ways of measuring exposure. In this study, length of service (duration of exposure), cumulative exposure to respirable dust and quartz and average intensity of exposure to respirable dust and quartz are used. All concentrations are based on 8 hour time weighted average (TWA) measurements.

Cumulative exposure

The sum (for all jobs) of years spent in a job multiplied by the average dust concentration of that job. Cumulative exposure can be calculated for respirable dust and quartz. The unit is milligram.years per cubic metre (mg.years/m^3).

Average intensity of exposure

Cumulative exposure for any individual divided by length of service. The unit is milligrams or micrograms per cubic metre (mg/m^3 or $\mu\text{g/m}^3$). (1 mg = 1000 μg).

Exposure response association

The association between exposure and the proportion of the sample of workers studied who show an adverse effect. In this report, this is the proportion of exposed goldminers with x-ray evidence of silicosis at different levels of exposure to respirable dust and quartz.

Job exposure matrix

Table of occupations and any other categorisation of interest, e.g. area or statistical population, to each item of which a value for time weighted average (TWA) respirable dust or quartz concentration is allocated. The matrix enables the allocation of values to empty cells (i.e. those for which there have been no measurements) on the basis of assumptions about the similarity of occupations or their role in the production process.

ILO Classification of the Radiographs of the Pneumoconioses (ILO classification)

Method for classifying chest x-rays of the pneumoconioses by comparison with standard x-ray films. Can be used to grade silicosis from normal to severe using a numeric scale.

1. Introduction

1.1 Objective

The primary objective of the study was to examine exposure response relationships between silica dust exposure and silicosis among black in-service goldminers.

Subsidiary objectives were to:

- ✍ Determine the prevalence of silicosis in older in-service black goldminers;
- ✍ Summarise dust exposure data for a range of goldmining occupations;
- ✍ Conduct a literature review of the prevalence of silicosis in South African goldminers as well as of exposure response relationships between silica exposure and silicosis internationally.

1.2 Methods

1.2.1 Review of relevant literature

A literature search was conducted to identify studies relevant to the prevalence of silicosis in South African goldminers as well as exposure-response relationships between silica exposure and silicosis.

1.2.2 Selection of a sample of employees for interview and medical examination

A target sample of 500 miners working at a mine near Orkney in the Free State who were 40 years of age or older were recruited to participate in the study. This age stratum was chosen as it was expected that most of these employees would have had 20 years or more of exposure to silica dust.

Employees were recruited consecutively into the study on their return from annual leave, when they normally undergo routine medical surveillance examinations. This procedure excluded employees on sick leave. In addition, employees on treatment for tuberculosis are discouraged from taking leave until treatment completion - such employees would thus be underrepresented in this sample.

A total of 520 employees eventually participated in the study, which was conducted from 27 November 2000 to 14 March 2001.

A detailed labour history was taken from each employee. This was compared with the company records immediately, allowing the subject to agree or disagree with these records. At a later date, these records were compared with those from The Employment Bureau of Africa (TEBA). If there were discrepancies, the employee was re-interviewed and the discrepancy resolved.

Miners were interviewed using an adapted version of the standardised American Thoracic Society (ATS) respiratory questionnaire, which inquired about respiratory symptoms, chest illnesses including tuberculosis, and smoking.

A full size posteroanterior (PA) chest x-ray was taken according to International Labour Organisation (ILO) specifications.

1.2. 3 Measurement of dust exposure

Two sets of dust data were used, one from a measurement study done as part of HEALTH 606 ("research data") and one derived from a routine database compiled by the company, the Integrated Risk Management System (IRMS) database. These are described below.

1.2.3.1 Research dust data

a. Selection of subjects for personal dust measurement

In order to measure quartz exposures in current jobs under research conditions, a cross sectional sample of 100 employees¹ was drawn from the mine. Mining takes place by rock breaking at a depth of 2100 metres. Production from stoping and developing currently amounts to over 220 000 tons per month.

There were 8707 employees on the mine engaged in approximately 2000 occupations in the year 2000. Of these about 13 occupations are "high dust" (of which 10 account for 96% percent of the employees in this category) and 35 are "medium dust" (of which 10 account for 90% percent of the employees in this category). The remaining 1 952 occupations (many of which have only one or two employees) are "low dust"².

The first 100 in a list of randomized employees of the mine were chosen. Of these, 59 came from the 13 high dust jobs, 34 from 30 of the medium dust occupations and 7 employees from 5 of the low dust occupations.

b. TWA dust measurement protocol, including quality assurance.

Pumps were serviced and calibrated to a flow rate of 1.9 l/min.³ The occupational hygiene practitioners involved in the exercise underwent a training session and were provided with a standard operating manual (*Strong and Dekker 2002*). Mineworkers in the selected sample were contacted in the week before the testing and requested to participate in the project. They were informed of all that was required of them, such as not tampering with the pumps, keeping the pumps away from water, etc. They were asked to sign consent that they agreed to participate. Pumps to be used underground were calibrated on the surface.

Personal samplers were worn at waist height for the full shift. Some shifts were longer and others shorter than 8 hours. Spot checks were carried out daily, but not all of the mineworkers participating in this study were necessarily checked every day.

¹ This group represented 26 occupations.

² The classification of the dust exposure categories was based on the judgement of two experienced hygienists familiar with the mine.

³ The maximum flow rate was 1.9 litres/ minute plus 5%.

Personal gravimetric full shift dust samples were to have been taken on all 100 miners for five consecutive shifts. A number of practical problems occurred during the dust collection. Some miners worked only three shifts during the study week, others declined to wear the samplers after a few shifts, and others were moved to alternative assignments during the week. Those who could not complete the full five shift measurements were replaced by the next employee down the list in the same occupation, making an eventual total of 112 workers and 506 dust measurements. Measurements were conducted between 10 July 2000 and 15 December 2000.

c. Analysis of dust for mass, respirable concentration and alpha quartz content

Gravimetric analysis of the 506 dust samples collected was carried out by the company Occupational Hygiene department using a standard method set out in a procedure manual prepared for the study (*Strong & Dekker 2000*)

The method for determination of alpha quartz used by Miningtek was developed by CSIR - MININGTEK [COMRO] (Chamber of Mines Research Organisation) and approved in 1991 by the S.A. Department of Minerals and Energy on the basis of comparisons carried out by the South African Bureau of Standards. The method uses x-ray diffraction and conforms in principle with the NIOSH 7500 method, except that the dust is analysed directly on a 25 mm mixed cellulose acetate filter.

Filters were pooled in batches of four or five by occupation prior to being sent for quartz analysis.

The data were captured onto an MS Excel spreadsheet, and calculations were done using the spreadsheet's functions. Dust concentrations collected during varying shift periods were converted to 8 hour TWA (respirable dust) concentrations. TWA quartz concentrations were calculated by applying the quartz fraction to the corresponding TWA respirable dust concentration.

It turned out that there were only 26 independent jobs on which dust readings had been taken, and these readings were tabulated by calculating the job-specific mean respirable dust and quartz TWA concentrations. Ventilation district and statistical population were not taken into account, as this would have resulted in too many gaps in the table.

As there were 85 jobs represented in the sample of 520 miners chosen for medical examination (see sec. 1.2.2 above) the research data had to be supplemented by data from the company's mandatory occupational hygiene dust surveillance programme, the IRMS database.

1.2.3.2 IRMS dust data

This step was an addition to the original protocol and involved the extraction of historical dust measurements from the IRMS database. This was done to supplement the measurements done as part of HEALTH 606 and to enable calculation of cumulative exposure for every employee in the survey.

a. Background to routine sampling, methods and description of the IRMS database.

The procedures for dust measurements and quality assurance within IRMS are set out in a written protocol (*Vermeijs 2002*).

In summary, employees are grouped into statistical populations according to assumed similarity of exposure. Five percent of each such population is sampled every 6 months (with a minimum of 5 samples). Sampling is spread over all working shifts by random sampling. Employees wear Gilian air pumps fitted with 25 mm diameter Gilian cyclones.

Calibration is done at the company Hygiene Laboratory on surface. During this process, the reference and sampling filters are weighed, the batteries fully charged, and the pump volume checked before the samplers are taken underground for sampling.

Gravimetric analysis is carried out on the mine by a trained occupational hygienist. Weighing of dust and reference filters is carried out in a weighing cabinet using two Model Sartorius R200D balances, to the fifth decimal point of a gram.

At least 5 samples from each statistical population are randomly selected and grouped for annual analysis of alpha quartz. Where there are over 200 persons in a population, a minimum of 2.5 percent of the samples is used for alpha quartz analysis. The method of quartz analysis is the same as described in the previous section.

The following information was extracted for the period 01/04/2000 to 30/12/2001: filter ID, sample date, employee number, occupation, TWA respirable dust concentration, quartz percentage, TWA quartz concentration. The mean sampling period per shift was 548 minutes (standard deviation 106 minutes).

The data were supplied as a Microsoft Excel spreadsheet of 715 records, which were selected from an original data set of some 7700 records.

The TWA concentrations for dust and quartz were calculated as for the research dust data, and a similar table constructed. For some observations the quartz in the dust was recorded as zero: i.e. the TWA concentration for respirable dust carries a nonzero value, while the corresponding value for quartz is zero.

1.2. 4 Development of job exposure matrix and estimation of cumulative exposure

The estimation of a job exposure matrix enables the attribution of a dust concentration to each occupational exposure category. For occupations or categories for which dust measurements are lacking, assumptions have to be made based on a knowledge of the relationship between jobs and the role of each job in the production process.

A job exposure matrix for dust and quartz was constructed by combining the data from the research and IRMS respirable dust and quartz tables. Where there was overlap – where both tables had values for a particular occupation – a simple average of these values was calculated.

a. Assignment of counts and reduction to occupations

As there were 59 occupations not represented in the job exposure matrix, equivalent jobs from within the matrix had to be found in order to assign dust and quartz values to each occupation. This was done by the *a priori* identification of equivalent jobs, and a dust concentration was thus attributable to each of the 2733 cumulative jobs that the 520 miners had held. There were 13 jobs unaccounted for in the 2733 - these were periods where the men had worked in coal mines (5), at other gold mines at a time when there were no computerised records (7), or at a platinum mine (1).

During this process, it was found that some of the jobs in both the research and IRMS dust data were in fact equivalent, further reducing the number of job categories for which dust readings were available to 22 (plus one category for zero dust); 11 from the research data, 5 from the IRMS data, and 6 from both. This is illustrated in Table 1.2.4.1

The following exposure variables were thus calculated:

Length of service is the sum of all contract days worked in each occupation;

Cumulative dust and *cumulative quartz* are the length of service in each job multiplied by the TWA concentration for dust or quartz respectively;

Average intensity is the cumulative dust or cumulative quartz divided by the length of service.

Table 1.2.4.1. TWA dust concentrations by exposure category and data source

TWA mean respirable dust concentration (mg/m ³)	Job title	Research data: Mean (SD) (mg/m ³)	No. of data points	IRMS data: Mean (SD) (mg/m ³)	No. of data points
0	Various - see below*	-	-	-	-
0.1	Plant hand	0.1	5		
0.126	Storeman underground			0.126 (0.085)	2
0.186	Onsetter or Onsetter's helper			0.186 (0.220)	4
0.340	Assistant underground	0.282 (0.283)	153	0.369 (0.492)	303
0.143	Lamp repairer			0.143 (--)	1
0.164	Sanitation minder, Helper			0.164 (0.189)	4
0.355	Engineering assistant	0.076 (0.032)	5	0.359 (0.395)	336
0.124	Survey / Sampling assistant	0.124 (0.083)	5		
0.287	Sanitation labourer	0.287 (0.281)	10		
0.106	Assistant surface	0.106 (0.069)	5		
0.248	Loco operator Loco driver	0.248 (0.253)	34		
0.219	Loader operator, Loader driver	0.104 (0.042)	5	0.301 (0.165)	7
0.484	Driller	0.484 (0.549)	90		
0.480	Winch operator	0.455 (0.650)	69	0.897 (0.752)	4
0.718	Miner's assistant	0.771 (0.785)	20	0.362 (0.319)	3
0.055	Chef/ Cook			0.055 (0.000)	6
0.14	Shiftboss assistant	0.14 (0.084)	5		
0.267	Crew supervisor	0.265 (0.291)	39	0.351 (--)	1
0.151	Boilermaker / Boilermaker's aide	0.151 (0.077)	10		
0.092	Fitter/ Fitter's aide	0.092 (0.054)	10		
0.484	General equipment & Construction team leader	0.484 (0.335)	5		
0.348	Team leader	0.473 (0.655)	23	0.283 (0.330)	44

SD: Standard Deviation

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* The following were deemed to have a dust and quartz exposure of 0:

Asset Protection (Security)
Bar Attendant Grade 1
Bar Supervisor
Clerk Grade 1
Compressor Minder
Crew Leader Surface
Driver-Light Vehicle (Cde8 Lic)
Fire Patrolman
Full-Time Union Steward
Gardener/Groundsman
Hoist Oper.(Rock) 150kw & Over
Messenger/Clerk
Mine Overseer
Painter-Unqualified
Procurements Assistant
Refrigeration Plant Operator
Stone Wall Mason
Storeman (Surface)
Technical Assistant - (T.D.S.)
Transport Officer

1.2. 5 Reading of chest x-rays

Chest radiographs were read into the ILO Classification of Chest Radiographs of the Pneumoconiosis (ILO Classification) by two experienced readers - both currently or previously certified by the National Institute for Occupational Safety Health (NIOSH), USA, as "B" readers, i.e. trained ILO readers.

Inter-reader agreement was analysed by examining percentage agreement and chance corrected agreement (kappa statistic).

1.2. 6 Statistical analysis

Frequency tabulations were carried out on all the exposure and outcome data as well as potential confounders such as age and history of tobacco smoking. The prevalence of reported tuberculosis (past) and current tuberculosis was also noted.

Histograms were constructed relating the prevalence of silicosis to length of service, and to cumulative exposure and average intensity for both respirable dust and quartz. For length of service, five year intervals were used in the graphical display. For the dust variables, the association was examined across quintiles of the exposure metric.

Logistic regression was used to examine exposure-response relationships formally. Models were run using a single radiographic definition of silicosis based on the presence of parenchymal small opacities of rounded or mixed rounded/irregular shape at an ILO profusion level of 1/1 and above. For both respirable dust and quartz, duration of exposure and average intensity were mutually adjusted. Age and a history of smoking were examined as potential confounders.

1.3 Ethical considerations

1. Value and relevance:

It is intended that answering the study questions will contribute new knowledge in the form of :

- ✍ Up to date silicosis prevalence data among in-service black goldminers;
- ✍ The first study of black mineworkers in South Africa relating silicosis prevalence to measures of exposure;
- ✍ Measurements of dust and quartz concentrations on a goldmine taken under research conditions to compare to dust measurements taken as part of routine dust surveillance for statutory purposes.

The findings can be expected to:

- ✍ Contribute evidence on the question of whether the current occupational exposure limit for quartz of 0.1 mg/m^3 is sufficiently protective against silicosis;
- ✍ Contribute to improved systems of dust measurement directed at disease risk reduction rather than routine statutory compliance;
- ✍ Contribute to measures to reduce the risk of silicosis among mineworkers, including dust control strategies and improved medical surveillance for silicosis.

2. Subjects had a full size chest x-ray (125kV), as opposed to the miniature chest x-ray they

would have had as a part of the routine medical surveillance.

3. The study was explained to each subject in his own language.
4. The only personal identifier on the database was the employee number. Analysis produced group summaries only.
5. Any employee found to have an abnormality was referred to the company clinical services for evaluation. Employees found to have compensatable pneumoconiosis were referred to the Medical Bureau for Occupational Diseases for assessment under the Occupational Diseases in Mines and Works Act.
6. No HIV testing was carried out.
7. Reporting is to SIMRAC, a tripartite structure, which will publicise the report on its website. An article will also be written for an international peer reviewed journal.
8. Stakeholders are identified as follows:
 - ✍ Safety in Mines Research Advisory Committee (SIMRAC) and its constituent committees;
 - ✍ Department of Minerals and Energy, including tripartite committees, particularly the Mining Occupational Health Advisory Committee (MOHAC);
 - ✍ The mining industry and mining unions;
 - ✍ Mining hygiene and safety professionals;
 - ✍ Occupational medicine and specialist practitioners and their associations: the Mine Medical Officers' Association, South African Society for Occupational Medicine, South African Pulmonology Society;
 - ✍ Medical Bureau for Occupational Diseases;
 - ✍ Academic and research organisations involved with mineworker health: including the National Centre for Occupational Health;
 - ✍ Non Governmental Organisations working with mining unions: e.g. Industrial Health Research Group.
9. Ethical approval was obtained from the Research Ethics Committee of the Health Sciences Faculty of the University of Witwatersrand, and from the Medical Research Ethics Committee of AngloGold Health Services.

2. Results

2.1 Literature review

2.1.1 Epidemiology of silicosis

Silicosis is the commonest form of pneumoconiosis in South Africa (*White 1995*). The high prevalence of silicosis relative to the other pneumoconioses reflects both the large numbers of people employed in dusty work in the South African gold mining industry (183 000 in 1998) (*White 2001*) and the toxicity of free crystalline silica. Silicosis is an incurable disease which can be prevented by limiting the inhalation of silica dust.

There are several different types of silicosis, viz. classic, accelerated and acute, which are distinguished by the degree of airborne concentration and length of exposure to the crystalline silica required to induce them, the speed with which they manifest and the degree to which lung tissue is replaced with fibrotic nodules. Classic "simple" silicosis is the result of low to moderate silica dust exposure over a number of years. Complications of simple silicosis include progressive massive fibrosis (PMF), loss of vital capacity, tuberculosis and lung cancer.

PMF is a rapid proliferation of nodules which form a stony mass of confluent nodules. The incidence among South African goldminers is not well documented, although cited as approximately 5 percent of cases of silicosis (*White 2001*). The factors known to cause the progression of simple silicosis to PMF are higher cumulative dust exposure, younger age at onset of pneumoconiosis, and continued dust exposure in the presence of simple pneumoconiosis (*White 1995*).

Evidence from a Canadian study of compensated silicotics suggests that simple silicosis does not affect life expectancy but that PMF may do so (*Infante-Rivard et al. 1989*). However, one cannot extrapolate directly from the Canadian context to that of South Africa given the paucity of the South African data on life expectancy and silicosis, and the very high prevalence of tuberculosis in South Africa which well may reduce life expectancy among silicotics (*White 1995*).

Even in the absence of PMF, progressive loss of vital capacity has been shown to be associated with simple silicosis, with the degree of annual decline associated with the extent of radiological profusion (*Cowie 1998, White 2001*).

The major complication of simple silicosis is an increased susceptibility to mycobacterial infections, especially tuberculosis (*Zambon 1987, Cowie 1994*). Two recent studies, one amongst Danish foundry workers (*Sherson and Landers 1990*) and the other in South African gold miners (*Cowie 1994*), have shown that workers with chronic silicosis have a three fold increase in the incidence of tuberculosis when compared with a group without silicosis matched for exposure and age. The incidence of active tuberculosis increases in direct proportion to the severity of the silicosis; the risk ratio for those with an International Labour Organisation (ILO) Classification small opacity profusion of 3/3 is comparable to the increased risk of tuberculosis in HIV infected subjects (*American Thoracic Society 1997*).

Even the earliest silicotic changes may carry an increased risk of tuberculosis (*Sluis-Cremer 1980*). Hnizdo and Murray undertook a study of the risk of tuberculosis relative to silicosis and silica exposure in which they found that even a negligible degree of silicosis (< 5 nodules at necropsy) was associated with an increased risk when compared with those without silicosis (*Hnizdo & Murray 1998*). However, the effect of silica dust rather than those few silicotic nodules may be the cause of the increased risk in this case.

The increasing prevalence of HIV infection in the country generally and among mineworkers in particular is likely to aggravate further an already serious situation given the increased susceptibility to tuberculosis among those with HIV infection. A recent study (*Corbett et al. 2000*) of the effect of HIV infection on silicosis and tuberculosis incidence in black South African gold mineworkers found that HIV infection increased the incidence of tuberculosis by five times and silicosis increased the incidence of tuberculosis by three times. The presence of both tuberculosis and silicosis increased the incidence of tuberculosis by fifteen times, so-called multiplicative interaction.

The association of silica, silicosis and lung cancer has been the subject of debate in recent years. Two recent authoritative reviews concluded that there were sufficient data to support an association between silicosis and lung cancer (*American Thoracic Society 1997, USA 2002*). However, more data are needed on the risk of lung cancer in non-smoking silicotics. Results from studies of white South African goldminers have been contradictory. Two earlier case-control studies showed no association between silicosis and lung cancer (*Hessel et al. 1986, Hessel et al. 1990*), in contrast to a later nested case-control study which demonstrated such an association (*Hnizdo et al. 1997*). In the latest study, Hnizdo et al. (1997) have argued that biases in the former two studies could account for the discrepancy. The risk of lung cancer in black mineworkers, who have historically smoked less than white mineworkers, is unknown.

In a recent editorial, Greaves (2000) has argued that the concept of "simple" silicosis needs revision in the modern era to take into account not only the well established risks of PMF and tuberculosis but also the newly established risk of lung cancer. In the context of the South African goldmining workforce, with its high and growing incidence of tuberculosis and the likely increase in the smoking habit among black mineworkers, this advice is doubly relevant. Silicosis cannot be regarded as a benign disease on the goldmines.

2.1.2 Prevalence of silicosis

Prevalence is the proportion of any given population with silicosis at the time of the survey. Prevalence gives an indication of the burden of disease in the population (whether in service or in a labour sending community) and the burden of likely complications, e.g. silicosis related tuberculosis, that might be expected. Prevalence can also be used to assess exposure-response relationships. Prevalence studies are relatively easy to do in working miners, but their interpretation must be tempered by a consideration of all the selection and information biases that may affect the data. Prevalence among in service miners does not take into account miners with silicosis who have left the workforce and those who develop silicosis after exposure has ended.

In order to predict the risk of an individual suffering from silicosis over the course of his working life, the average risk for that class of worker has to be inferred from following up a cohort of workers that share similar exposure and other characteristics. This risk, i.e. *cumulative incidence*, for any given exposure (years of service or cumulative dust exposure) is inferred from statistical modelling of cohort data. The only South African studies to have

done such modelling are on white miners and are described in the next section (*Beadle et al. 1971, Beadle 1977, Hnizdo & Sluis-Cremer 1993*).

Compensation based data, such as reports from the Medical Bureau for Occupational Diseases, reflect the experience of only those who have had access to the compensation system. Such data can offer information on trends over time, assuming stable access to the compensation system, but suffer from too many biases to be able to infer true risk.

2.1.2.1 Prevalence of silicosis among in service workers

Remarkably, there is very little information available on the prevalence of in service workers on the goldmines. Despite the fact that black mineworkers have historically performed the dustiest jobs on the mines, there is no study of exposure response relationships in this group of workers. Cowie and Van Schalkwyk (1987) calculated a prevalence of silicosis among in-service workers on a Free State gold mine of 0.9 percent (9 per 1000 workers) based on a miniature radiography survey. When the authors used the total number of cases detected on the mine in a year, the prevalence was slightly higher at 1.34 percent (13.4 per 1000 workers). The authors did not relate the prevalence figures to length of service nor exposure and the results are thus of limited value in inferring risk.

The authors discuss a number of difficulties in obtaining an accurate estimate of the prevalence of the silicosis in the workforce, all of which would tend to result in an underestimate. Some of these difficulties they relate to the migrant labour system and large annual turnover of contracts (at that time). However, they also suggest that because of the statutory system of certifying workers with silicosis as unfit for underground work, some of the older workers may have avoided routine radiology for fear of losing their livelihood.

There are also reasons why the prevalence of silicosis among black mineworkers may have risen since Cowie and Van Schalkwyk reported their findings. The average length of service of black mineworkers has increased over time as labour contracts have been stabilised, a phenomenon dated from the mid 1970s (near the beginning of the period covered in this study) (*Leger 1989, 1991, White 1995, Murray et al. 1996*). The consequences of stabilisation of the workforce would be to increase the length of service and thus cumulative dust exposure of black miners and to improve the detection rate of silicosis which is more likely to manifest in later working life.

Murray et al. (1996) analysed statutory autopsy data on over 16 000 black gold miners who had died of non-natural causes (assumed to be unrelated to silicosis) while in service over the period 1975 to 1991. This group was on average younger and with shorter length of service than the typical workforce. An overall prevalence of 9.7 percent of histological silicosis was found, of which 1.2 percent was classified as "moderate to severe" histological silicosis. There was a trend to increasing histological silicosis prevalence of all grades from 9.3 percent in 1975 to 12.8 percent in 1991 (and in moderate to severe histological silicosis from 0.3 percent to 1.2 percent). Since chest x-rays are likely to pick up only a fraction of histological silicosis, these findings are not necessarily incompatible with those of Cowie and Van Schalkwyk. Strikingly, the length of service in most of the cases was under 15 years.

2.1.2.2 Prevalence of silicosis among former gold miners

There is also a paucity of data pertaining to the occupational health of black former mineworkers. Leger (1989, 1991) pieced together fragmentary evidence available from a

number of incomplete data sets which indicated that there was a neglected epidemic of pneumoconiosis and tuberculosis among former mineworkers.

Steen et al. (1997) undertook a prevalence survey of occupational lung disease amongst a random sample of former gold mineworkers in the Kweneng district of Botswana. The researchers demonstrated a significant burden of pneumoconiosis and found an overall prevalence of pneumoconiosis [? profusion 1/0 on the International Labour Organisation (ILO) scale] of 25.7 percent in the random arm of the study.

Trapido et al (1998) carried out a prevalence study of occupational lung disease in a random sample of former mineworkers in the Libode district of the Eastern Cape Province. The overall prevalence of pneumoconiosis (? 1/0, ILO) was highly dependent on reader, with one reader finding 22 percent and the other 36 percent. Significant associations between length of mine service and pneumoconiosis and also between reduced FEV1 and FVC and pneumoconiosis were found in both of the above studies.

Twenty five percent of the Libode study subjects were found to be eligible for compensation. A review of the records of the Compensation Commissioner for Occupational Diseases showed that 68 percent of those eligible for compensation had never been compensated. A total of 30 percent had been compensated before but disease progression made them eligible for an additional payment. Only two percent had been paid in full and were entitled to no additional compensation.

Trapido et al. (1998) estimated the costs of gold mining related occupational lung disease to the mining industry, the state health services and the mine labour sending communities. The extent of the unpaid liability of occupational lung disease compensation was shown to be considerable with much of the cost of this disease externalised by the mining industry.

2.1.3 Exposure response associations

In mining, the mechanical disintegration of matter that results in dust is generated predominantly during the breaking up, transportation and comminution of rock. The key dust-generating activities in mining are drilling, blasting and mechanical loading (*Du Toit 1968*). The extent to which dust generated in mine work poses a health risk is determined by four interlinked factors: particle size, mineralogical composition, concentration, and duration of exposure (*Workplace Information Group 1995*).

In order for dust to create a risk for developing an occupational lung disease it must be deposited in the lung alveoli. There are a range of pulmonary defence mechanisms which prevent this from happening and as a result not all dust that is inhaled is a health hazard. In particular, only dust particles that are small enough ($< 5 - 7 \mu\text{m}$) to penetrate the alveolar region of the lung pose a health risk (*Lippmann 1983*). It is thought that the exact distribution of particle sizes deposited in alveoli in relation to total inhaled dust will vary depending on the curves initially recommended by the British Medical Research Council in 1952, a standard that was subsequently adopted by the Johannesburg International Conference on Pneumoconiosis in 1959 (*Orenstein 1967*). Based on these curves, dust measuring equipment has been developed to collect particles within the respirable dust range.

The mineral composition of dust particles varies by mine type and not all respirable dust causes reaction in lung tissue. In gold mines the key health hazard in dust is biologically active, free crystalline silica, a compound of silicon and oxygen. The spatial arrangement of

the silicon atoms determines the different forms of silica. The commonest form of crystalline silica is quartz. Hnizdo (1991) has suggested that the high rate of silicosis peculiar to the Witwatersrand gold mines is in part due to the exceptionally high silica content of the reef formations, in that about 60 to 80 percent of virgin rock is bound silica and approximately 30 percent of respirable mine dust is free silica.

2.1.3.1 Silicosis and average intensity of exposure (mean lifetime concentration)

The concentration of dust particles is an important determinant of health risk. Various terms are used in different jurisdictions for the legally or administratively allowable concentration of airborne dust, including Occupational Exposure Limit (OEL), Threshold Limit Value (TLV), Recommended Exposure Limit (REL) and Permissible Exposure Limit (PEL). The best known internationally are probably the TLVs published by the American Conference of Governmental Industrial Hygienists (ACGIH), based on knowledge acquired in animal experimentation and through occupational epidemiology. The TLV may be defined as a time weighted average (TWA) concentration for an 8 hour day and a 40 hour week to which most workers can be exposed over a working lifetime without adverse health effects.

The current OEL (the term used in South Africa) as regulated by the Department of Minerals and Energy for respirable silica is 0.1 mg/m^3 . A value of 0.1 mg/m^3 is also the exposure limit legislated by the Occupational Safety and Health Act (OSHA) and Mine Health and Safety Act (MSHA) in the United States (USA 2002). [This latter is expressed in the formula $10/(\text{percentage quartz} + 2)$, using a value of 100 percent quartz].

The concept of an OEL has been criticised. OELs are based on a normal respiration rate rather than the increased respiration rate that occurs with hard physical labour that characterises the South African mines. Consequently the OEL formula may fail to protect South African mineworkers adequately (*Workplace Information Group 1995*). Unsted (personal communication) has criticised the TLV standard for failing to take account of the non silica fraction in mine dust and the health implications of such dust. Unsted has argued that given the variable quartz content of airborne dust, it is important to minimise exposure to dust as a whole rather than single out silica.

It is difficult to establish the precise relationship between exposure to silica dust and the subsequent development of silicosis. However, the literature on the subject has recently been reviewed in detail by the National Institute for Occupational Safety and Health (NIOSH) in the United States (USA 2002). The reviewers summarised the cumulative incidence (or prevalence) of silicosis (defined as ILO category $\geq 1/1$) over a 45-year lifetime based on different mean respirable quartz concentrations. Some of the specific risk estimates are derived from Rice and Stayner (1995).

Of the studies of goldminers, three (*Hnizdo & Sluis-Cremer 1993, Kreiss & Zhen 1996, Steenland & Brown 1995*) show a very high risk of silicosis at a mean concentration of 0.1 mg/m^3 over a working lifetime. The findings of a recent cohort study (*Chen et al. 2001*) not included in that review are in accord with this conclusion. The Hnizdo and Sluis-Cremer (1993) study of South African miners in fact predicts that 70 percent of miners would eventually develop silicosis at this level (*Rice & Stayner 1995*).

Even at half this level, i.e. a mean quartz concentration of 0.05 mg/m^3 , these studies predict that a still significant fraction of the workforce would develop silicosis (13 percent in the Hnizdo and Sluis-Cremer study, 10 percent in the Steenland and Brown study and as high as 30

percent in the Kreiss and Zhen study). The exception to this finding is from the study of Canadian gold and uranium (Muir *et al* 1989a, 1989b, Muir 1994), which predicts that a mean of 0.05 mg/m^3 would be almost wholly protective against silicosis.

Various hypotheses have been put forward for the difference in risk between the Canadian and South African studies, including dust measurement inaccuracies and variation in the quartz content or even fibrogenicity of the ore (Muir 1994, Hnizdo 1994, Hughes & Weill 1995). Another difference between the studies is greater length of follow up in the South African study. There is conclusive evidence that silicosis progresses or may appear for the first time many years after the cessation of silica exposure (Hnizdo & Sluis-Cremer 1993, Steenland & Brown 1995, Chen *et al.* 2001). The longer the follow up, the greater will be the percentage of the cohort diagnosed with silicosis.

Much of the risk assessment literature in recent years has focused on the relationship between silica, silicosis and lung cancer (Greaves 2000, Sherson 2002, Wong 2002). The growing body of evidence indicates that a standard of 0.1 mg/mg^3 , for a 45 year working life, will result in a significant burden of not only radiological silicosis, but also death from silicosis and lung cancer (t Mannetje *et al.* 2002, Rice & Stayner 1995). The evidence is not sufficient to establish whether a level of even 0.05 mg/m^3 is protective (Rice & Stayner 1995).

As a result of these and other studies, NIOSH and the ACGIH have recommended a silica standard of 0.05 mg/m^3 (USA 2002). Calls to lower the OEL for silica to 0.05 mg/m^3 (Sherson 2002) and even to 0.01 mg/m^3 (Greaves 2000) have been made in the international scientific literature on the basis of reviewed evidence.

2.1.3.2 Silicosis and cumulative exposure

In his historic work, Beadle *et al.* (1971) related data from dust samples (collected by konimeter), with work histories and medical data in a cohort of white South African workers. This cohort started employment between 1934 and 1938, with no known occupational dust exposure outside the gold mines and had worked at least 3000 shifts. The data suggested that after 3000 shifts (approximately 10 years) there was a risk of silicosis of two percent and after 9000 shifts (i.e. approximately 30 years) a cumulative risk of silicosis of 40 percent (Beadle *et al.* 1971).

Hnizdo and Sluis-Cremer (1993) subsequently used Beadle's dust measurements to relate dust exposure to a set of chest x-rays taken from a more extensive cohort of workers with a longer follow up period, and covering a slightly later historical period, viz. the early 1940s to the early 1970s. On the assumption that the dust contained 30 percent silica, the Hnizdo and Sluis-Cremer study found that the cumulative risk of developing silicosis increased from approximately 0.5 percent at a cumulative exposure of 1 mg.years/m^3 of silica to 25 percent at 2.7 mg.years/m^3 and exponentially to 77 percent at 4.5 mg.years/m^3 (calculated from Fig. 2 of that report).

The cumulative exposure response associations from four studies with follow up after leaving exposure have been summarised by Chen *et al.* (2001). These cohorts are the white South African goldminers (Hnizdo & Sluis-Cremer 1993), Colorado hard rock miners (Kreiss & Zhen 1996), South Dakota goldminers (Steenland & Brown 1995) and Chinese tin miners (Chen *et al.* 2001). A close concordance is apparent in the exposure response associations of the South African goldminers, South Dakota goldminers and Chinese tin miners across the range 0.0 to 3.0 mg.years/m^3 of quartz, with some divergence at the highest exposure levels. The outlier is the Colorado hard rock miner study which shows cumulative risks of silicosis

approximately double that of the South African study at low and mid range exposures, with convergence only at very high cumulative exposures.

2.1.3.3 Quality of exposure data

All the above studies are based on the assumption that if a goldminer is exposed to 0.1 mg/m^3 in a standard working year the cumulative exposure would be 0.1 mg.years/m^3 . However, the concept of a standard working year is problematic given that there is wide variability and peaks in dust exposure within a shift (*Unsted 1998*). There are also variations in quartz concentration of respirable dust over time as there are variable concentrations of quartz in the ore body (*Unsted, personal communication*).

Furthermore, studies undertaken using animal experiments (*Bolton et al. 1983, Klosterkotter & Bunemann 1961*) suggest that lung clearance mechanisms change when the lung burden (i.e. the amount of a given substance that exists in the lung) exceeds a given threshold and that there is a slower rate of clearance associated with such an overload than that of normal pulmonary clearance. Averaging dust levels may thus not properly reflect biologically significant exposure when one is trying to assess the relationship between silica dust exposure and the subsequent development of silicosis.

Reliance cannot be placed on the South African studies cited above to assess current risk of silicosis for a number of reasons. The report of the Leon Commission (*Republic of South Africa 1995*) pointed out that data relating to dust levels "still relies heavily on the original studies carried out by Beadle and amplified and commented on by Du Toit, Hnizdo and King and cited in evidence to the Commission by White and Leger". Such data must be treated with caution because they rely on a study that is almost 40 years old and an untested assumption that dust levels have not changed in this time period.

Further, the measurements for the Beadle study were made on white miners. Historically, legally enforced job reservation excluded the majority of black workers from all but the dustiest jobs. If Beadle's exposure data are used to generalise across all workers, it would be on the basis of the untenable assumption that exposure to dust did not and does not differ between these two groups of workers. Further, white workers have been predominantly, although not entirely, employed in supervisory positions and consequently have had a constant low level of exposure rather than the variable exposure with high peaks that characterises stope workers.

In order to test the effectiveness of dust control strategies and to identify high risk groups, there is a need for new studies of the incidence and prevalence of occupational lung disease in South African mineworkers in relation to dust exposure, using gravimetric dust measuring tools to obtain accurate assessment of exposure.

2.2 Univariate description of research (Health 606) dust and IRMS dust data

In the research dust dataset, the median TWA respirable dust concentration was 0.17 mg/m³, with a range of 0.05 to 3.71 mg/m³ (Table 2.2.1 below).

The median quartz fraction was 13.2 percent, well below the 30 percent used in the study by Hnizdo for white miners (*Hnizdo and Sluis-Cremer 1993, Hnizdo 1994*), based on work by Beadle (*Beadle and Bradley 1971*).

Of particular interest is that the median respirable quartz concentration was 0.019 mg/m³, and the 75th percentile (not shown in table) 0.065 mg/m³, both below the current OEL for quartz in the mining industry of 0.1 mg/m³.

Table 2.2.1 Dust concentrations and alpha quartz percentage : HEALTH 606 measurements*

	N	Mean	Std dev.	Median	Range
TWA respirable dust concentration (mg/m ³)	506	0.35	0.46	0.17	0.05 – 3.71
Alpha quartz fraction (%)**	497*	12.0	5.6	13.2	0 – 21.3
TWA respirable quartz concentration (mg/m ³)	497	0.048	0.072	0.019	0 – 0.71

TWA: 8 hour time weighted average. Std dev.: standard deviation

* The distribution of occupations was approximately 59% high dust, 34% medium dust and 7% low dust (see sec. 1.2.3.1 above).

**Following pooling of batches of dust samples by occupation. Alpha quartz fraction for that batch attributed to each sample in the batch.

The IRMS measurements (for a partly different range of jobs, with some overlap) (Table 2.2.2 below) were a little higher than those of the routine data set above. For example, the median TWA dust concentration was 0.22 mg/m³ (compared to 0.17 mg/m³), but with a wider range. The quartz fraction was 16.1 percent, also with a wider range. The median TWA quartz concentration was 0.028 mg/m³, compared to 0.019 mg/m³, with an identical range.

Table 2.2.2 Dust concentrations and alpha quartz percentage: IRMS (routine) dust measurements

	N	Mean	Std dev.	Median	Range
TWA respirable dust concentration (mg/m ³)	715	0.36	0.44	0.22	0.022 - 4.29
Alpha quartz fraction (%)	655*	16.0	5.8	16.1	0.67 - 39.1
TWA respirable quartz concentration (µg/m ³)	715	0.051	0.072	0.028	0 - 0.71

TWA: 8 hour time weighted average. Std dev.: standard deviation

*Following pooling of batches of dust samples by occupation. Alpha quartz fraction for that batch attributed to each sample in the batch.

2.3. Univariate description of workforce examined and of exposure characteristics

In keeping with the sampling strategy of including older, long service workers, the mean age was 46.7 years, the youngest being 37.1 years (Table 2.3.1). The range of length of service was from 6.3 years to 34.5 years, with a mean of 21.8 years. The median number of jobs per subject was five.

Of note is the low average intensity of exposure. For respirable dust, the highest average intensity was 0.7 mg/m^3 , with 90 percent of the workers having an average intensity of between 0.24 and 0.48 mg/m^3 . This range is well below the Occupational Safety and Health Act (OSHA), USA, and Mine Safety and Health Act (MSHA) USA, exposure limit for silica containing respirable dust of 0.65 mg/m^3 . This is based on a quartz fraction of 13.2 percent using the formula $10 / (\% \text{ quartz} + 2)$, (USA 2002) (See section 2.1).

For quartz, the highest average intensity was 0.095 mg/m^3 . Thus all of the employees had an average intensity below the current occupational exposure limit of 0.1 mg/m^3 .

Table 2.3.1 Age and exposure characteristics of study sample (n = 520)

	Mean	Std dev.	Median	5th-95th percentile	Range
Age (years)	46.7	4.4	46.1	40.8 - 54.7	37.1 – 59.9
Duration of exposure (years)	21.8	5.3	21.9	13.1 – 30.6	6.3 – 34.5
Number of jobs	-	-	5	-	1 – 16
Cumulative exposure respirable dust (mg.years/m^3)	8.2	2.88	7.95	4.0 - 13.2	0 – 22.68
Average intensity respirable dust (mg/m^3)	0.37	0.096	0.36	0.24 – 0.48	0 - .70
Cumulative exposure respirable quartz (mg.years/m^3)	1.15	0.43	1.12	0.51 – 1.91	0 - 3.08
Average intensity respirable quartz (mg/m^3)	0.053	0.015	0.051	0.029 – 0.075	0 – 0.095

Just over half of the sample had ever smoked, with 37 percent being current smokers (Table 2.3.2). A total of 101 subjects (19.4 percent) reported having had tuberculosis in the past and nine workers had active tuberculosis at the time of the study.

Table 2.3.2 Smoking and tuberculosis status of study sample (N = 520)

	N	% of sample
Ever smoked	266	51.1
Current smokers (N = 420 responses)	150	37.3
Ever TB (self-reported)	101	19.4
TB now	9	1.7

2.4 Silicosis prevalence and inter-reader reliability

2.4.1 Prevalence of radiological abnormality

Most of the films were of good ILO quality or with defects not likely to interfere with the reading of pneumoconiosis. The readers differed in their assignment of quality, with reader one more likely to record a higher quality than reader two. Ten films were declared to be unreadable by one or both readers.

Table 2.4.1 Film quality by reader (ILO classification)

Film quality	Reader 1		Reader 2	
	N	%	N	%
1	369	71%	240	46%
2	128	25%	223	43%
3	18	3%	50	10%
4	5	1%	7	1%
Total	520	100%	520	100%

For simplicity in what follows, the results for reader one will be cited, with those for reader two following in parentheses, unless indicated otherwise.

Strikingly, only 43.5 percent (38.8 percent) of films were assessed as completely normal (Table 2.4.2). A total of 28.9 percent (29.9 percent) had abnormalities other than diffuse parenchymal opacities (i.e. ILO profusion = 0/0, but other abnormality).

Table 2.4.2 Overall reading of any abnormality by reader

	Reader 1		Reader 2	
	N	%	N	%
Unreadable	5	1.3%	7	1.3%
Completely normal	226	43.5%	202	38.8%
Abnormality other than diffuse parenchymal	150	28.9%	155	29.9%
Diffuse parenchymal abnormality*	139	26.7%	156	30.0%
Total	520	100%	520	100%

* Includes ILO profusion = 0/1

Using the radiological definition of profusion 1/0 or above, of the 515 films assessed as readable by reader one, 23.9 percent [95% confidence interval (CI) 20.3 – 27.8] had a

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profusion of 1/0 or more (Table 2.4.4). The equivalent prevalence for reader two was 23.2 percent (95% CI 19.6 – 27.1).

Using an ILO cut point of 1/1 or above, the prevalence of silicosis as assessed by reader one was 18.3 percent (95 % CI 15.0 - 21.9) and by reader two 19.9 percent (95% CI 16.5 – 23.6) (Table 2.4.3). The prevalence using either cut point was thus very close for the two readers.

Notably, of the 94 films making up the reader one's prevalence of 18.3 percent overall, 49 were read in the more severe profusion categories 2 or 3, i.e. 9.5 percent overall. (Of the 102 films identified with silicosis by reader two, 53 or 10.4 percent overall were in profusion categories 2 or 3).

Table 2.4.3 Classification of parenchymal abnormality by reader, minor ILO categories

ILO category	Reader 1		Reader 2	
	N	%	N	%
0/0	376	73.0%	357	69.6%
0/1	16	3.1%	37	7.2%
1/0	29	5.6%	17	3.3%
1/1	27		33	
1/2	18		16	
2/1	14		19	
2/2	19		22	
2/3	9		6	
3/2	2		5	
3/3	5		1	
Subtotal $\geq 1/1$	94	18.3%	102	19.9%
Total	515	100%	513	100%

Excludes unreadable films.

Table 2.4.4 presents the same data as Table 2.4.3 but aggregated by ILO major profusion category.

Table 2.4.4 Classification of parenchymal abnormality by reader, major ILO categories

ILO category	Reader 1		Reader 2	
	N	%	N	%
0	392	76.1%	394	76.8%
1*	74	14.4%	66	12.9%
2	42	8.2%	47	9.2%
3	7	1.3%	6	1.2%
Subtotal ≥ 1	123	23.9%	119	23.2%**
Total	515	100%	513	100**%

*Includes profusion 1/0

** Slight rounding error

The symbols q and r predominated as the primary size/shape symbol (Table 2.4.5). Reader one hardly made use of the s/t/u categories of irregular opacities for the primary size/shape symbol. By contrast, reader two made more frequent use of these categories.

Table 2.4.5 Primary size/shape symbol on ILO classification by reader

Symbol	Reader 1		Reader 2	
	N	%	N	%
p	-	-	1	1
q	85	61	81	52
r	53	38	51	33
s	-	-	10	6
t	1	1	10	6
u	-	-	3	2
Total	139	100	156	100

2.4.2 Agreement between readers

There was a high level of agreement between the two readers. Using the lower 3 minor ILO categories (0/0, 0/1 and 1/0) and aggregating the rest, the percentage agreement was 82%, with a kappa = 0.59 (95% CI 0.53 – 0.65), indicating good agreement (Table 2.4.6).

Table 2.4.6 Agreement between readers using lowest 3 ILO categories plus aggregated category > 1/0

Reader 2	Reader 1				
		0/0	0/1	1/0	>1/0
0/0	330	18	10	14	372
0/1	12	3	1	0	16
1/0	8	11	3	7	29
>1/0	4	5	3	81	93
	354	37	17	102	510

This agreement improved further in using a dichotomous scale (Table 2.4.7). For a cut point of 1/0, concordance was 89.6 percent, with a kappa of 0.71 (95% CI 0.62 - 0.80) indicating excellent agreement. Agreement was even better using a 1/1 cut off [percentage agreement = 93.5%, kappa = 0.79 (0.70 – 0.88), signifying excellent agreement].

Table 2.4.7 Agreement between readers using dichotomous ILO scale (cutpoint 1/0 or 1/1)

		Reader 2		
		< 1/0	≥1/0	
Reader 1	<1/0	363	25	
	≥1/0	28	94	
				510
		<1/1	≥1/1	
	<1/1	396	21	
	≥1/1	12	81	
				510

2.5 Exposure response relationships (graphical display)

The associations between different exposure variables and silicosis prevalence are illustrated in Figures 2.5.1 – 2.5.5 in Appendix 1.

Figure 2.5.1 shows a very low prevalence of silicosis among the group with 15 years of service or less – only 1.6 percent (one out of 59 workers in that group). Prevalence rises steadily thereafter, however, reaching 32 percent among workers with over 30 years of service. The test for linear trend was highly significant ($p = 0.00$). A threshold ("Lowest Adverse Effect Level") for the appearance of radiological silicosis is thus apparent at around 15 years of exposure in this group of employed miners.

A similar rising trend in silicosis prevalence is observed in relation to cumulative exposure of both respirable dust (Fig. 2.5.2) and quartz (Fig. 2.5.3) ($p = 0.00$ for trend in both cases). Of note is the limited range of cumulative exposure (with some aggregation of the highest categories, so that the range is less than in Table 2.3.1) : approximately 0 to 22 mg.years/m³ for respirable dust and 0 to 3.0 mg.years/m³ for quartz.

A non-significant trend to increasing silicosis prevalence is observed for average intensity of respirable dust ($p = 0.053$ for trend) (Fig. 2.5.4). A non-significant trend is similarly observable for average quartz intensity ($p = 0.06$) (Fig. 2.5.5).

2.6 Exposure response relationships (logistic regression modelling)

The association between silicosis and each of the exposure variables was examined in separate logistic regression models. These have greater statistical power to examine trends than the grouped data in the graphical display, as the exposure variables are treated as continuous variables. The odds ratio for each of the exposure variables is presented in Table 2.6.1.

Because of the small numerical increment represented by one year of service, the odds ratio for a five year increment in service is also presented. Similarly for average intensity, the odds ratio refers to an increment of ten micrograms (0.01 mg/m^3).

Table 2.6.1 Association between silicosis and each of the exposure variables in logistic regression*

	Odds ratio	95% confidence interval	p
Length of service (per year)*	1.11	1.06 – 1.17	0.00
Length of service (per 5 years)*	1.69	1.34 – 2.15	0.00
Cumulative exposure:dust (per $\text{mg}\cdot\text{year}/\text{m}^3$)	1.2	1.1 – 1.3	0.00
Cumulative exposure:quartz (per $\text{mg}\cdot\text{year}/\text{m}^3$)	3.2	1.9 – 5.4	0.00
Average intensity: dust (per $10 \text{ }\mu\text{g}/\text{m}^3$)*	1.03	1.005 – 1.05	0.02
Average intensity: quartz (per $10 \text{ }\mu\text{g}/\text{m}^3$)*	1.18	1.02 – 1.37	0.03

*Length of service and average intensity mutually adjusted. Cumulative exposure examined in a model on its own.

A statistically significant trend is observable for each exposure metric. For example, for each $\text{mg}\cdot\text{year}/\text{m}^3$ of cumulative quartz exposure, there is an increase in the odds of silicosis by 3.2. This trend is stronger than for respirable dust (odds ratio = 1.2).

Similarly, the odds ratio for each increment of $10 \text{ }\mu\text{g}/\text{m}^3$ in quartz concentration is 1.18, compared to 1.03 for respirable dust concentration.

A total of 51.1 percent of the sample had ever smoked. Neither age nor having ever smoked were independent predictors of silicosis in exploratory analysis. No adjustment was therefore carried out for these variables.

As tuberculosis is not an independent risk factor for silicosis no adjustment was carried out for this variable.

3. Discussion

3.1 Prevalence of silicosis

The prevalence of silicosis among in service black goldminers over 37 years of age on this mine in 2000 was found to be 18.3 percent (using reader one's findings). The 95 percent confidence interval around this estimate is 15.0 to 21.9 percent. Silicosis was measured radiologically using the 1/1 ILO cutpoint for profusion, which is more specific for disease than the 1/0 cutpoint. Further, approximately half of the films read as silicosis were at the 2 or 3 level of profusion on the ILO scale, indicating a relatively severe average degree of pneumoconiosis.

The sample consisted of all miners (who met the age requirement) arriving sequentially over a period of six months for routine medical surveillance on their return from annual leave. They are thus likely to be adequately representative of the whole workforce in this age stratum. (Mineworkers with active tuberculosis are discouraged from taking leave and would therefore be underrepresented in the sample. Given the association between silicosis and tuberculosis, their exclusion may have reduced the observed silicosis prevalence.)

There was very high agreement between two experienced chest x-ray readers, indicating excellent reliability.

This study updates the only other published figures of prevalence among black goldminers of 1.34 percent from a workforce survey in 1984 (*Cowie & Van Schalkwyk 1987*) and of 9.3 percent to 12.8 percent histological silicosis in an autopsy series covering the period 1975-1991 (*Murray et al. 1996*). The earlier estimate included all miners, irrespective of length of service, which would have significantly diluted the prevalence estimate. In the current study only workers over 37 years of age were studied to make it more efficient to examine exposure response relationships. Ninety-five percent of the subjects had over 13 years of service. Short service workers were thus largely excluded. If a sample representing the whole workforce had been included, the prevalence of silicosis would have been lower.

However, another likely reason for the large difference in silicosis prevalence between the two reports is the impact of stabilisation of the black workforce, and hence increase in length of service, on the goldmines as argued by Leger (1989, 1991) and illustrated in White (1995) and Murray et al. (1996). If this process of stabilisation started in the mid 1970s, then almost all the exposure of the workforce studied (mean length of service 21.9 years) would have fallen into this period of stabilisation.

Even a prevalence of 18.3 percent must be regarded as an underestimate of the prevalence in the true underlying cohort of men over 37 years of age. The sample studied came from a "healthy survivor" cohort, in that workers found to have second degree pneumoconiosis (mainly silicosis plus tuberculosis) are required by law to be barred from further risk work. They would thus not be available for study.

In addition, prevalence underestimates lifetime cumulative incidence ("true risk"). It is well established that quartz exposure carries a lifelong risk of incident (newly appearing) silicosis even after exposure has ceased (*Hnizdo & Sluis-Cremer 1993, Chen et al. 2001*). Such cases would also not be captured in this study.

Indirect evidence of this "externalised" risk among black goldminers comes from comparing the prevalence in this study to that found in two survivor populations of ex-miners studied in their home districts (Steen *et al.* 1997, Trapido *et al.* 1998). The prevalence in the Trapido *et al.* study ($\geq 1/1$, calculated from Table II of that paper) was 26.3 percent (reader one) and 20.6 percent (reader two), comparable to but greater than the figure in this study.

In the Steen *et al.* study, only the prevalence $\geq 1/0$ level and above was provided. The prevalence in the random arm of that study was 25.7 percent, comparable to 23.9 percent (reader one, $1/0$ and above) in this study.

3.2 Exposure response relationships

Using the prevalence data, exposure response relationships were estimated for five exposure metrics: length of service, cumulative exposure to respirable dust, cumulative exposure to respirable quartz, average intensity of exposure to respirable dust and average intensity of exposure to respirable quartz. The quality of these exposure data needs to be considered.

3.2.1 Length of service

Length of service ranged from 6.3 to 34.5 years (with 90 percent lying between 13.0 and 30.5 years) providing a wide gradient for exposure response analysis. Self-reporting of length of service was validated against company records and discrepancies cleared up. The quality of this exposure variable is thus likely to have been high.

There was only one case of silicosis in the group with under 15 years of exposure. However, this cannot be interpreted as a threshold since there is no information on how many workers with less than 15 years of service had left mining work because of silicosis, or the subsequent incidence of new silicosis appearing in this shorter service subcohort after they had left mining work. This finding should be compared to that of Murray *et al.* (1996) who found a prevalence of 9.7 percent histological silicosis in an autopsy series of black goldminers most of whom had had fewer than 15 years of service. However, only 1.2 percent were classified as moderate to severe histological silicosis.

3.2.2 Dust exposure data

Dust exposure data are far more problematic than duration of exposure. No historical dust data were available for this cohort. It was thus not possible to construct a true historical cumulative exposure record. Contemporary dust measurements, including both gravimetric sampling and quartz fraction analysis, were used instead.

To interpret this as reflection of working lifetime exposure, the assumption has to be made that current dust concentrations are a reasonable proxy for average dust concentrations experienced in those jobs over the previous three decades, and similarly for average quartz fractions.

There is partial evidence for this assumption. The Leon Commission of Inquiry into Safety and Health in the Mining Industry (*Republic of South Africa 1994*) concluded that there was no evidence of any reduction in exposure to dust over the previous forty years. [A similar assumption regarding the periods 1936 to 1960 and 1940 to 1970 had been incorporated into earlier studies of white goldminers (Beadle 1971, Page-Shipp & Harris 1972, Hnizdo 1994)]. A

report by Du Toit (1991) found respirable dust concentrations in eleven goldmining occupations somewhat higher than those reported by Beadle (reproduced in *White 1995*). A recent autopsy study, based on data pertaining to the period 1975-1991, showed no statistically significant trend in the prevalence of silicosis due to factors other than increasing age and years of service (*Murray et al. 1996*). However, data on the more recent period 1970 to 2000, and particularly for the mine studied, are needed to test this assumption critically.

If, however, there was in reality a downward secular trend in dust concentrations on the mine, then an exposure response association calculated on the basis of contemporary measurements would *overestimate* the risk at any given exposure. This is because any silicosis present would appear to be caused by lower dust exposures than was truly the case.

Another assumption was required by the allocation of contemporary dust measurements collected for a given occupation to all instances of that occupation listed in the work history of each individual. It was assumed that the dust concentration collected for (say) a driller's assistant in a particular ventilation district or shaft in the research study was representative of that of a driller's assistant in any other ventilation district or shaft.

Further assumptions were made in the grouping together of occupations believed to represent similar exposures, in order to assign exposures to occupations not represented in either of the dust databases. This grouping was done on the basis of the opinion of an occupational hygienist familiar with the mine.

Quartz fractions were calculated by x-ray diffraction for both the HEALTH 606 study and the IRMS database by the same laboratory. Quartz fractions may vary over time and from shaft to shaft, requiring the assumption that average quartz fractions used in the study are a reasonable proxy for historical quartz fractions.

Besides the question of the historical and cross-occupational representativeness of the dust data, the dust measurement process itself is subject to error. For the HEALTH 606 substudy gravimetrically measured TWA dust concentrations were obtained for 26 occupations under controlled research conditions. For the IRMS data used to supplement the dust data obtained in the HEALTH 606 study, reliance was placed on the company's routine quality control system for ensuring the accuracy of its measurements. (*Strong and Dekker 2000, Vermeij 2000*) However, the effect of measurement error that is independent of the presence of silicosis, as is likely here, is to dilute rather than to exaggerate exposure response effects.

3.2.3 Exposure response associations

An important feature of the study was the very narrow range of average intensity of exposure for both respirable dust and quartz. For respirable dust exposure, 90 percent of the values for average intensity fell between 0.24 and 0.48 mg/m³. This range is entirely below the OSHA and MSHA exposure limit for quartz using the formula 10/(quartz fraction plus 2) assuming a quartz fraction of 13.2 percent. Similarly, for the average intensity of quartz, 90 percent of the values fell between 0.029 and 0.075 mg/m³, all well below the OEL of 0.1 mg/m³.

The implication is that almost all of the mineworkers studied had worked below the OEL for silica. Despite working in the protective range, 18.3 percent of these older mineworkers had developed silicosis.

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A crude linear trend to increasing prevalence with increasing exposure was noted for all the exposure metrics. The association was stronger for quartz than for respirable dust, a finding compatible with the biological effect of the quartz component in producing lung fibrosis.

The strength of the effect is reflected in the prevalence odds ratio, although this measure also depends on the unit used for the exposure metric. For cumulative quartz, an increment in one $\text{mg}\cdot\text{year}/\text{m}^3$ (across a narrow range up to $2.2 \text{ mg}\cdot\text{years}/\text{m}^3$) produced a 3.2 times increase in silicosis prevalence.

For length of service, the odds ratio for a 5 year increment in service was 1.7, i.e. a 70 percent increase in prevalence, across a wide range of lengths of service. For average quartz intensity, the odds ratio for a $10 \mu\text{g}$ (0.01 mg) increment was 1.18, i.e. an 18 percent increase, across a narrow range.

Despite the limitations of a prevalence survey, it is interesting to compare the prevalence figure obtained with earlier estimates of incidence among white South African goldminers derived in exposure response studies (*Beadle et al. 1971, Hnizdo & Sluis-Cremer. 1993*). Beadle's cohort was exposed between the 1930s and 1960s, while Hnizdo's was in service between the early 1940s and early 1970s. Both eras predate the calendar period of exposure of the group studied in this report.

Using length of service as the predictor, the current study found a prevalence of 22 percent among workers in the stratum with a length of service of 20.1 - 25 years (Table 2.6.1). After approximately 22.5 years of service (the stratum midpoint) the Beadle model predicts the incidence of silicosis as 10 percent or below on any of the dose response curves he developed (each based on an average konimeter reading, ranging from 800 to 1800 ppcc) (*Beadle et al. 1971*). It would take closer to 30 years on his highest dust concentration curve to reach an incidence of silicosis of 22 percent.

King (1986) used the Beadle data to model the risk of silicosis for black underground mineworkers (specifically drillers), incorporating an adjustment for the historical observation that black mineworkers acquired silicosis in only 60 percent of the time of that recorded for white mineworkers. Using King's curve based on the lowest average dust concentration (1300 ppcc in Figure 17 of her monograph), after 22.5 years of service the risk of silicosis would be approximately 18 percent. This is closer to but still below the prevalence of 22 percent in the stratum with the equivalent length of service in this study.

For cumulative exposure, a comparison can be made with the Hnizdo & Sluis-Cremer study (1993) of white mineworkers. These authors used cumulative respirable dust exposure as the exposure metric (i.e. respirable dust after treatment with heat and acid). In that cohort the mean cumulative respirable dust exposure ($6.6 \text{ mg}\cdot\text{years}/\text{m}^3$) and average intensity ($0.29 \text{ mg}/\text{m}^3$) were lower than in this study ($7.95 \text{ mg}\cdot\text{years}/\text{m}^3$ and $0.36 \text{ mg}/\text{m}^3$ respectively). However, that cohort was followed up for a further 20 years after exposure ceased. Hnizdo and Sluis-Cremer developed a curve of cumulative incidence against cumulative dust exposure (Table IV and Figure 1 of their paper).

Table 3.2.3.1 Comparison of exposure-response association in this study with that of a study of white mineworkers

Cumulative respirable dust exposure (mg.years/m ³)*	Cumulative incidence (%) (Hnizdo & Sluis-Cremer 1993)	Prevalence (%) (this study)
3.0	-	10
6.5	7	11
8.0	18	12.5
9.5	32	22.5
16.5	>82**	35

* Midpoint of prevalence stratum from Fig. 2.5.2 in Appendix 1

** Based on very few cases

In the lower cumulative exposure strata, the prevalence values in this study are higher than the cumulative incidence figures. However, from about the mean cumulative exposure value of 8 mg.years/m³, the cumulative incidence figures are higher and in the highest stratum very much higher.

The discrepancy between the two curves emphasises the importance of proper follow up in order to characterise accurately the risk of silicosis in a cohort. In the Hnizdo and Sluis-Cremer study, the onset of 57 percent of the 313 cases of silicosis occurred after the miners had left the mines, as these white miners returned at intervals for chest x-rays for compensation purposes.

The prevalence figure in this study is thus certainly an underestimate of cumulative incidence. There is no reason to believe that if black miners selected out of the underlying cohort because of second degree compensatable disease were counted and those who left service for any reason were followed up for the same period and to the same degree as in the Hnizdo and Sluis-Cremer study, the cumulative incidence in this cohort of black mineworkers would be any less than found in the latter study. In fact, given the higher cumulative dust exposures of this cohort, the prediction is that the overall cumulative incidence would be higher than that described among white mineworkers.

Finally, with regard to respirable quartz (rather than respirable dust), the median value in this study was approximately 0.05 mg/m³ (the occupational exposure limit recommended by the National Institute of Occupational Safety and Health and the TLV of the American Conference of Governmental Industrial Hygienists), with a range below 0.1 mg/m³, the OEL used in the South African mining industry. The slopes of the exposure response curves for average intensity were rather flat compared to that for length of service. This is confirmed in Table 2.6.1 by the lower odds ratio for 10 μ g/m³ increments in quartz intensity than for 5 year increments of exposure. This suggests that within the narrow range of dust concentrations experienced by these goldminers, duration of exposure is the more important determinant of silicosis risk.

3.2.4 Quartz fraction

The mean quartz fraction in this study was of the order of 12 to 16 percent (depending on data source), with a wide range. This mean is about that half the 30 percent assumed by Hnizdo (*Hnizdo & Sluis-Cremer 1993, Hnizdo 1994*), based on the work of Beadle and Bradley (1971). Beadle and Bradley had in fact found the mean quartz fraction to be 27.8 percent (range 14 to 57 percent) of total airborne dust. Hnizdo applied this fraction to respirable dust (*Hnizdo 1994*).

The discrepancy most likely reflects the fact that in this study only one mine was sampled at one time period. However, if Hnizdo's quartz fraction were an overestimate, then any exposure response association derived in the Hnizdo & Sluis-Cremer study for quartz dust based on the formula 0.3 times the respirable dust concentration would understate the risk at any given exposure.

3.3 Conclusions

This is the first study of exposure response relationships for silicosis in black South African goldminers using dust exposure data. The main findings are:

1. Almost one in five of these older, longer service black mineworkers had developed silicosis. This finding points to the urgent need for improved dust control to reduce silica exposure in this workforce.
2. Allowing for the fact that the sample in this study was chosen to represent older mineworkers, if one extrapolates these results to the goldmining industry in general, they confirm the existence of a significant epidemic of silicosis in the industry and a concomitant need for dust reduction strategies.
3. Within the narrow range of average dust concentrations, duration of exposure is a strong determinant of the risk of silicosis. This implies that as the average contracts of service of black mineworkers lengthen, as they have been doing over the past three decades, the burden of silicosis will rise.
4. If the assumption of stability of average dust concentrations on this mine over the past 30 years is correct, these workers developed silicosis despite having been exposed to a mean quartz concentration below the recommended occupational exposure limit of 0.1 mg/m^3 . This is in accord with a mounting body of evidence that an OEL of 0.1 mg/m^3 is not at all protective against silicosis.
5. The data suggest that an OEL of 0.05 mg/m^3 would not be protective against silicosis either. However, no exposure threshold could be determined as the many sources of measurement variability and assumptions in grouping the dust data make distinctions between relatively small increments in average quartz intensity subject to error.
6. The findings support the conclusion of Hnizdo and Sluis-Cremer ten years ago, as well as that of NIOSH (see literature review) that a reduction of the OEL from 0.1 mg/m^3 is indicated to reduce substantially the risk of silicosis. Both that study and the current one suggest that a reduction to at least 0.05 mg/m^3 will be necessary to achieve such protection.

4. References

- American Thoracic Society. 1997.** Adverse effects of crystalline silica exposure. *American Journal Respiratory and Critical Care Medicine*, 155:761-765.
- Beadle, D.G. 1971.** Recent progress in dust control in South African gold mines. In: Shapiro HA, editor. Proceedings of the International Conference on Pneumoconiosis, Jan.20-25; Johannesburg, Oxford:Pergamon,
- Beadle, D.G., Harris, E. & Sluis-Cremer, G.K. 1971.** The relationship between the amount of dust breathed and the incidence of silicosis: an epidemiological study of South African European gold miners. In: Shapiro HA, editor. Pneumoconiosis: Proceedings of the International Conference, Johannesburg. Oxford: Pergamon, 473-477.
- Beadle, D.G. & Bradley. 1971.** The composition of airborne dust in South African goldmines. In: Shapiro HA, editor. Pneumoconiosis: Proceedings of the International Conference, Johannesburg. Oxford: Pergamon, 462-466.
- Beadle, D.G. 1977.** The relationship between the amount of dust breathed and the development of radiological signs of silicosis: An epidemiological study of SA gold miners. In Walton, WH (ed.). Inhaled Particles IV, part 2. Oxford, Pergamon Press, 953-964.
- Bolton, R.E., Vincent, J.H., Jones, A.D., Addusib, J. & Beckett, S.T. 1983.** Hypothesis for pulmonary clearance of UICC amosite fibres inhaled by rats. *British Journal of Industrial Medicine*, 40:264-272.
- Chen, W., Zhuang Z, Attfield, M.D., Chen, B.T., Gao, P., Harrison, J.C., Fu, C., Chen, J-Q. & Wallace, W.E. 2001.** Exposure to silica and silicosis among tin miners in China: exposure-response analyses and risk assessment. *Occupational and Environmental Medicine*, 58:31-37.
- Corbett, E.L., Churchyard, G.J., Clayton, T.C., Williams, B.G., Mulder, D., Hayes, R.J, & De Cock, K.M. 2000.** HIV infection and silicosis: The impact of two potent risk factors on incidence of mycobacterial disease in South African miners. *AIDS* 14:2759-2768.
- Cowie, R.L. & van Schalkwyk, M.G. 1987.** The prevalence of silicosis in Orange Free State gold miners. *Journal of Occupational Medicine*, 29:44-46.
- Cowie, R.L. 1998.** The influence of silicosis on deteriorating lung function in gold miners. *Chest*, 113:340-343.
- Cowie, R.L. 1994.** The epidemiology of tuberculosis in gold miners with silicosis. *American Journal of Respiratory Critical Care Medicine*. 150; 1460-1462.
- Du Toit, R.S.J. 1968.** The functional relationship between dust hazard and the rate of collecting funds to pay compensation for pneumoconiosis [PhD thesis].Johannesburg: University of the Witwatersrand, 1968.
- Du Toit, R.S.J. 1991.** The shift mean respirable mass concentration of eleven occupations of Witwatersrand gold miners. Johannesburg: National Centre for Occupational Health Report No. 4/91.

Greaves , I.A. 2000. Not-so-simple silicosis: a case for public health action. *American Journal of Industrial Medicine*, 37:245-251.

Hessel, P.A., Sluis-Cremer, G.K. & Hnizdo, E. 1986. Case-control study of silicosis, silica exposure and lung cancer in white South African gold miners. *American Journal of Industrial Medicine*, 10:57-62.

Hessel, P.A., Sluis-Cremer, G.K. & Hnizdo, E. 1990. Silica exposure, silicosis and lung cancer: a necropsy study. *British Journal of Industrial Medicine*, 47:4-9.

Hnizdo, E. 1991. Combined effect of dust exposure and tobacco smoke on the occurrence of lung diseases in South African gold mines [PhD thesis]. Johannesburg: University of the Witwatersrand.

Hnizdo, E. & Sluis-Cremer, G. 1993. Risk of silicosis in a cohort of white South African gold miners. *American Journal of Industrial Medicine*, 24:447-457.

Hnizdo, E. 1994. Risk of silicosis in relation to fraction of respirable quartz (Letter to the editor). *American Journal of Industrial Medicine* 25: 771-77.

Hnizdo, E., Murray, J. & Klempman, S. 1997. Lung cancer in relation to exposure to silica dust, silicosis and uranium production in South African gold miners. *Thorax*, 52:271-375.

Hnizdo, E. & Murray, J. 1998. Risk of pulmonary tuberculosis relative to silicosis and exposure to silica dust in South African gold miners. *Occupational and Environmental Medicine*. 55, 496-502.

Hughes, J.M. & Weill, H. 1995. Silicosis risk: Canadian and South African miners (Letter to the editor). *American Journal of Industrial Medicine* 27: 617-618.

Infante-Rivard, C., Armstrong, B., Ernst, P., Petitclerc, M., Cloutier, L-G. & Theriault, G. 1989. A descriptive study of prognostic factors influencing survival of compensated silicotics. *American Review of Respiratory Disease*, 44: 1070-1074.

Kreiss, K. & Zhen, B. 1996. Risk of silicosis in a Colorado mining community. *American Journal of Industrial Medicine*, 30:529-539.

King, R. 1986. Silicosis in South African gold mines. A study of the risk of disease of black mineworkers. Draft paper (unpublished). Technology Advisory Group/Wits Sociology Research.

Klosterkotter, W. & Bunemann, G. 1961. Animal experiments and the elimination of inhaled dust. In: Dodgson J, McCallum RI, editors. *Inhaled Particles and Vapours III*. Oxford: Pergamon Press, 327-337.

Leger, J.P. 1989. Occupational disease in South African mines - a neglected epidemic. *South African Medical Journal*, 76:557-561.

Leger, J-P. 1991. Labour market changes and occupational disease consequences in South African mining. Association for Sociology of South Africa Annual Congress, Cape Town, 1-3 July, pp.1-9.

Lippmann, M. 1983. Size selective health hazard sampling. In: PJ Lioy, editor. Air Sampling Instruments for the Evaluation of Atmospheric Contaminants. 6th rev. ed. Chicago: American Conference of Governmental Industrial Hygienists :1-19.

Muir, D. Shannon, C.F., Julian, H.N., Verma, A., Sebastien, K.K. & Bernholz, C.D. 1989a. Silica exposure and silicosis among Ontario hardrock miners: Methodology. *American Journal of Industrial Medicine*, 16:5-11.

Muir, D. Shannon, C.F., Julian, H.N., Verma, A., Sebastien, K.K. & Bernholz, C.D. 1989b. Silica exposure and silicosis among Ontario hardrock miners: Analysis and risk estimates . *American Journal of Industrial Medicine*, 16:29-43.

Muir, D.C.F. 1994. Toxicity of silica dust (Letter to the editor). *American Journal of Industrial Medicine*, 25:769-770.

Murray, J., Kielkowski, D. & Reid, P. 1996. Occupational disease trends in black South African gold miners. An autopsy based study. *American Journal of Respiratory Critical Care Medicine*, 153:706-710.

Orenstein, A.J., editor. 1967. Proceedings of the Pneumoconiosis Conference, Johannesburg, March 30-31, 1959. London: A&J Churchill, Ltd.

Page-Shipp, R.J. & Harris, E. 1972. A study of dust exposure of South African white gold miners. *Journal of the South African Institute of Mining and Metallurgy*, 73:10-24.

Republic of South Africa. 1995. The Commission of Inquiry into Health and Safety in the Mining Industry. Leon RN, chairperson. Pretoria: Department of Minerals and Energy.

Rice, F.L. & Stayner, L.T. 1995. Assessment of silicosis risk for occupational exposure to crystalline silica. *Scandinavian Journal of Work, Environment and Health*, 21 Suppl. 2: 87-90.

Sherson, D. & Landers, F. 1990. Morbidity of tuberculosis among silicotic and non silicotic foundry workers in Denmark. *Journal of Occupational Medicine*, 2: 110-113.

Sherson, D. 2002. Silicosis in the twenty first century. *Occupational and Environmental Medicine*, 59: 721-722.

Sluis-Cremer, G.K. 1980. Active pulmonary tuberculosis discovered at post mortem examination of the lungs of black mineworkers. *British Journal of Chest Disease*, 74: 374-8.

Steen, T.W., Gyi, K.M. White, N.W., Gaabosianelwe, T., Ludick S., Mazonde G.N., Mabongo, N., Ncube, M., Monare, N., Ehrlich, R.I. & Schierhout, G. 1997. Prevalence of occupational lung disease among Botswana men formerly employed in the South African mining industry. *Occupational Environmental Medicine*, 54: 19-26.

Steenland, N.K. & Brown, D. 1995. Silicosis among gold miners; exposure - response analysis and risk assessment. *American Journal of Public Health*, 85:1372-77.

Strong, A.L. & Dekker, J.J. 2000. Simhealth 606: Gravimetric dust sampling quality control manual. Angolgold (internal document).

't Mannetje, A., Steenland, K., Attfield, M., Boffetta, P., Checkoway, H. & DeKlerk, N.

2002. Exposure response analysis and risk assessment for silica and silicosis mortality in a pooled analysis of six cohorts. *Occupational and Environmental Medicine*, 59:723-728

Trapido, A., Mqoqi, N.P., Williams, G., White, N., Solomon, A., Macheke, C., Goode, R. & Panter, C. 1998. Prevalence of occupational lung disease in a random sample of former mineworkers, Libode District, Eastern Cape Province, South Africa. *American Journal of Industrial Medicine*. 34:305-313.

Trapido, A., Goode, R. & White, N. 1998. Costs of occupational lung disease in the South African mining industry. *Journal of Mineral Policy, Business and the Environment*, 13: 26-33.

Trapido, A. 1998. An overview of the literature pertaining to silica dust, occupational lung disease and former mineworkers in the South African gold mining industry. Report prepared for Aurum Health Research.

USA. Department of Health and Human Services, National Institute of Occupational Safety and Health. 2002. NIOSH Hazard Review: Health effects of occupational exposure to respirable crystalline silica. DHSS (NIOSH) Publication No. 2002-129.

Unsted, A.D. 1998. Gravimetric dust sampling for control purposes and occupational dust sampling. *Journal of the Mine Ventilation Society of South Africa*, 51(1):24-30.

Vermeijs, M.M. 2002. Gravimetric Sampling Strategy, 01/04/2002 – 30/09/2002. Working Environment Management Department, Great Nologwa Mine (internal document).

White, N. 1995. Health hazards in the mining industry: an overview. A submission to the Commission of inquiry into Health and Safety in the Mining Industry. Leon RN, chairperson. Pretoria: Department of Mineral and Energy.

White, N. 2001. Occupational Lung Disease. In: Guild, Ehrlich, Johnston & Ross, eds. Handbook of Occupational Health Practice in the South African Mining Industry. Johannesburg: Safety In Mines Research Advisory Committee, 119-151.

Wong, O. 2002. The epidemiology of silica, silicosis and lung cancer: some recent findings and future challenges. *Annals of Epidemiology*, 12:285-287.

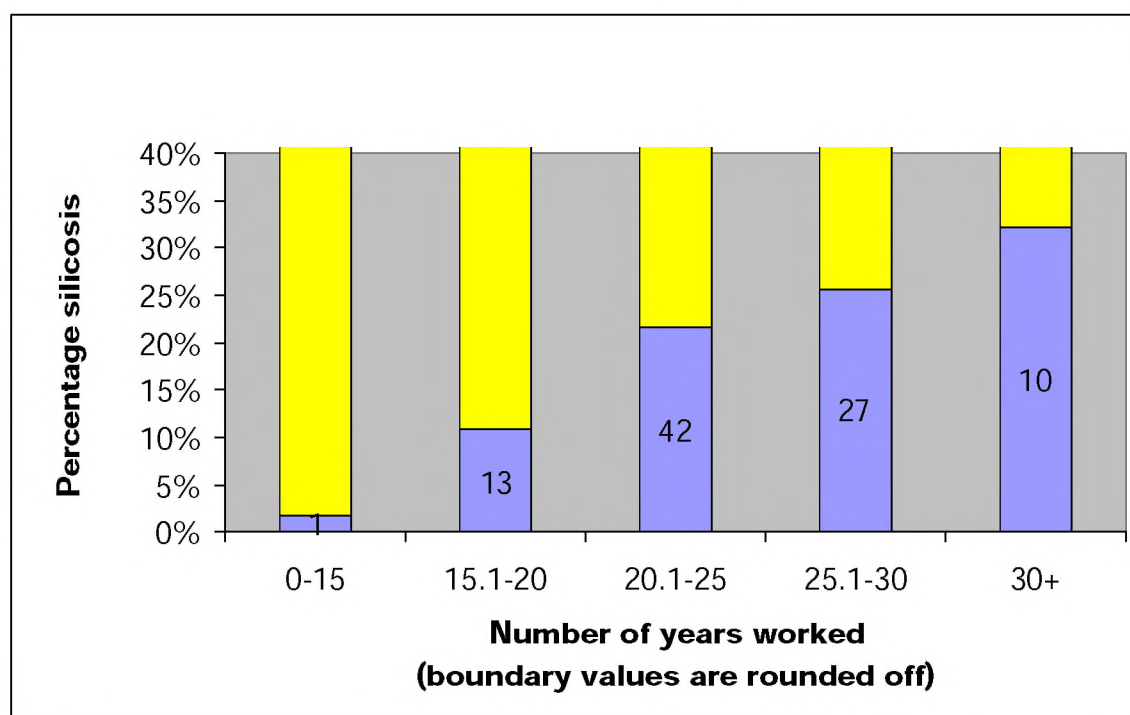
Workplace Information Group. 1995. Dust in the mines. A submission to the Commission of Inquiry into Health and Safety in the Mining Industry. Leon RN, chairperson. Pretoria: Department of Mineral and Energy.

Zambon, P. 1987. Mortality of workers compensated for silicosis during the period 1959-1983 in the Veneto Region of Italy. *Scandinavian Journal of Work Environment and Health*, 13:118-123.

APPENDIX 1

Prevalence of silicosis by various exposure metrics

Figure 2.5.1: Prevalence of silicosis by length of service

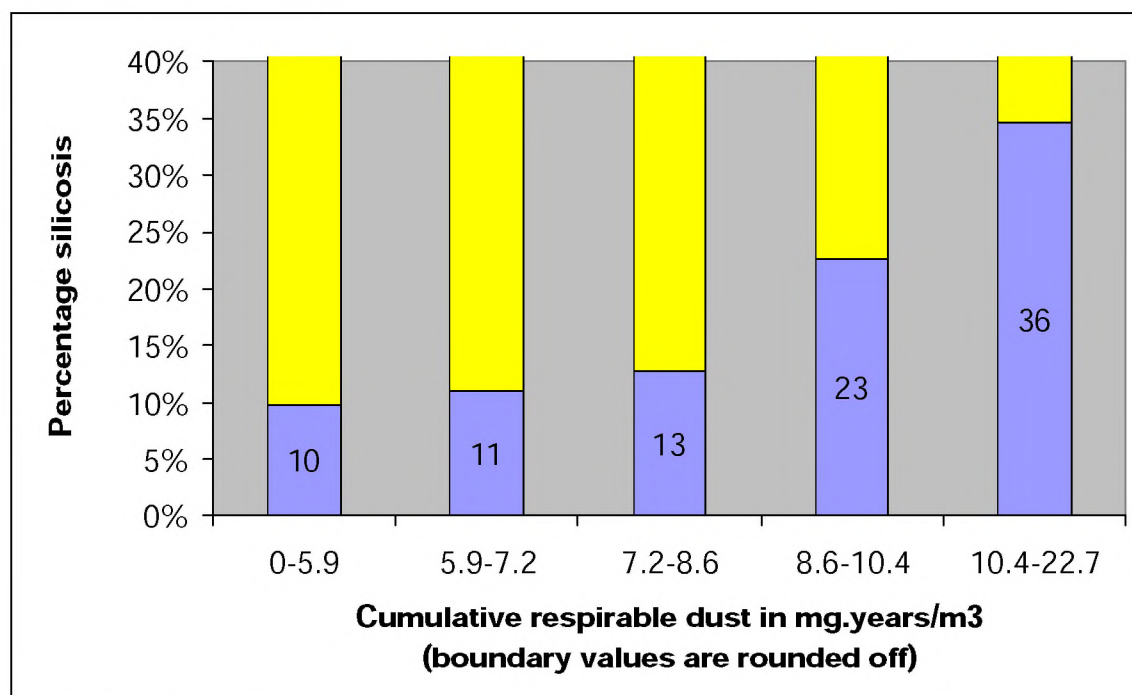


Number of cases is given in each bar.

Trend in silicosis prevalence across groups is significant.

Score test for trend of odds: $\text{Chi}^2(1) = 23.51$; $p = 0.0000$

Figure 2.5.2: Prevalence of silicosis by cumulative respirable dust exposure, in quintiles

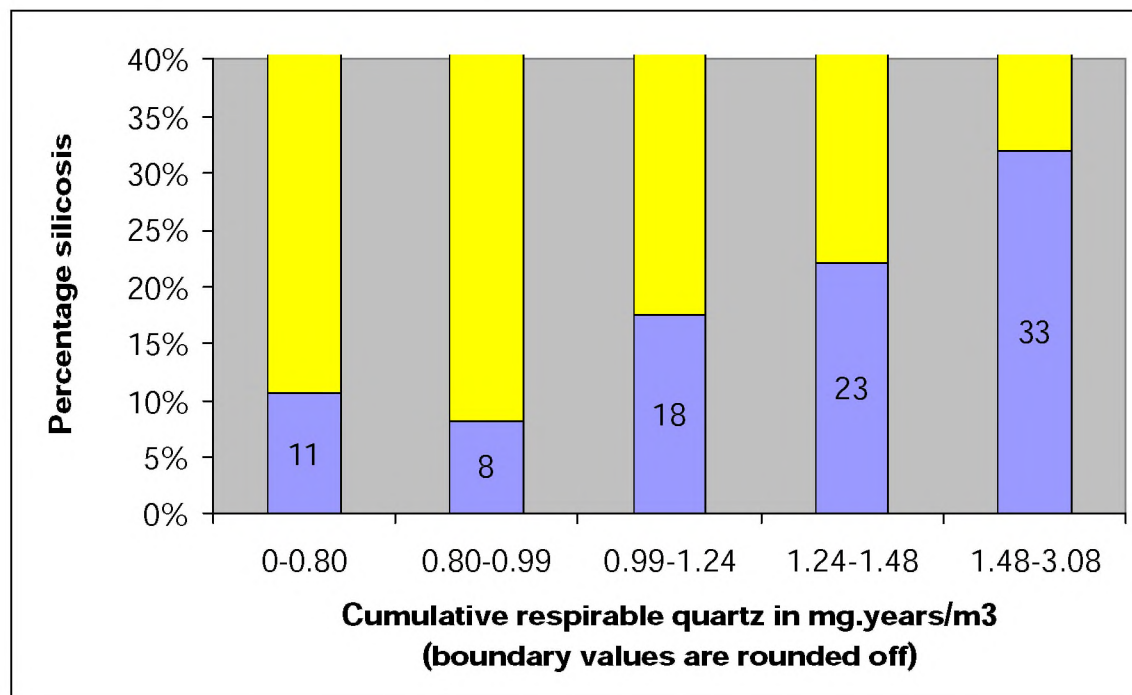


Number of cases is given in each bar.

Trend in silicosis prevalence across groups is significant

Score test for trend of odds: $\chi^2(1) = 25.82$; $p = 0.0000$

Figure 2.5.3: Prevalence of silicosis by cumulative quartz exposure, in quintiles

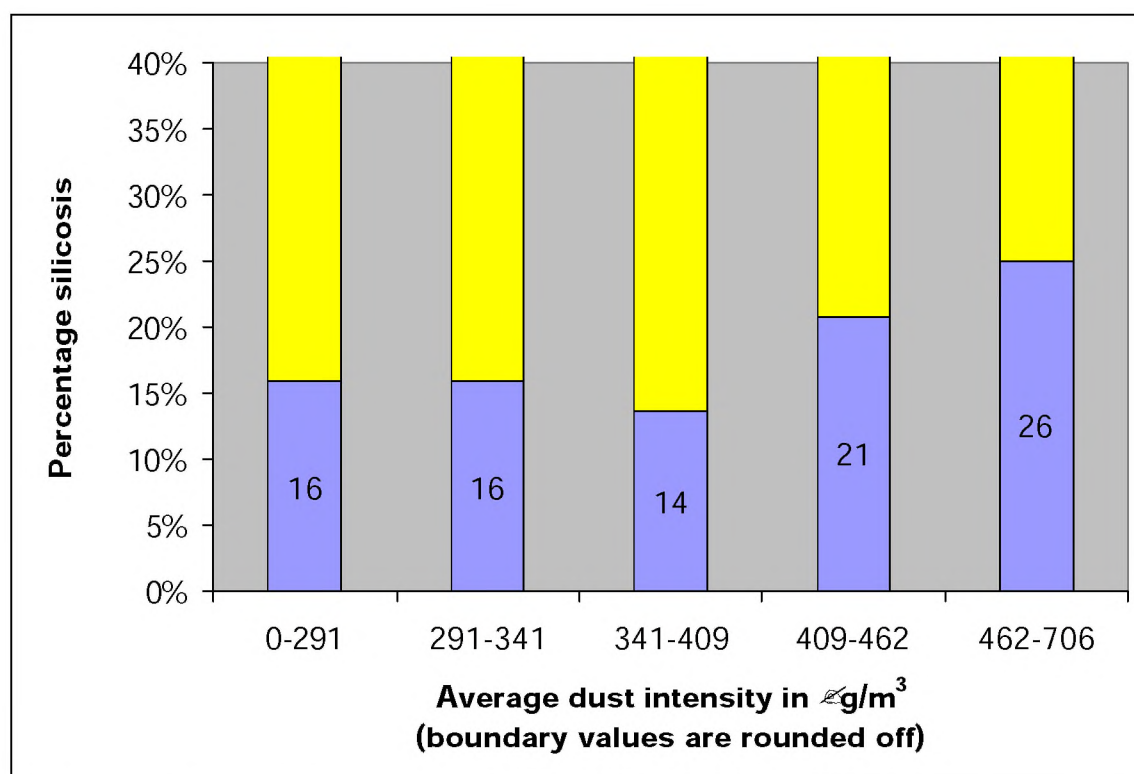


Number of cases is given in each bar.

Trend in silicosis prevalence across groups is significant

Score test for trend of odds: $\chi^2(1) = 21.76$; $p = 0.0000$

Figure 2.5.4: Prevalence of silicosis by average respirable dust exposure, in quintiles

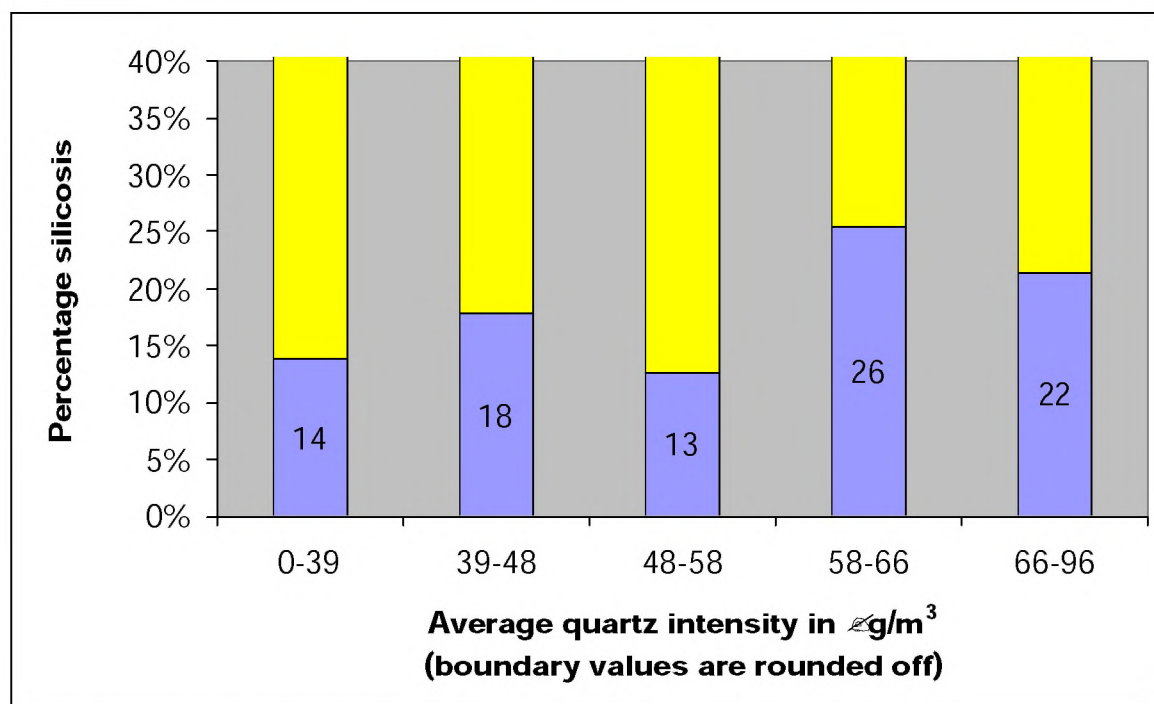


Number of cases is given in each bar.

Trend in silicosis prevalence across groups is not significant

Score test for trend of odds: $\chi^2(1) = 3.74$; $p = 0.0530$

Figure 2.5.5: Prevalence of silicosis by average quartz exposure, in quintiles



Number of cases is given in each bar.

Trend in silicosis prevalence across groups is not significant

Score test for trend of odds: $\chi^2(1) = 3.50$; $p = 0.0613$