Lung function loss in relation to silica dust exposure in South African gold miners

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ABSTRACT

Objective To estimate exposure-response relationships between respirable dust, respirable quartz and lung function loss in black South African gold miners.

Methods 520 mineworkers aged >37 years were enrolled in a cross-sectional study. Gravimetric dust measurements were used to calculate cumulative respirable dust and quartz exposures. Excess lung function loss was defined as predicted minus observed forced expiratory volume in one second (FEV_1) and forced vital capacity (FVC). The association between excess loss and exposure was estimated, adjusting for smoking, tuberculosis and silicosis.

Results Mean service length was 21.8 years, mean respirable dust 0.37 mg/m^3 and mean respirable quartz 0.053 mg/m^3. After adjustment, 1 mg-yr/m^3 increase in cumulative respirable dust exposure was associated with 18.7 ml mean excess loss in FVC [95% confidence interval (CI) 0.3, 37.1] and 16.2 ml in FEV1 (95% CI -0.3, 32.6). Mean excess loss with silicosis was 224.1 ml in FEV1 and 123.6 ml in FVC; with tuberculosis 347.4 ml in FEV1 and 264.3 ml in FVC.

Conclusion Despite a healthy worker effect, lung function loss was demonstrable whether due to silicosis, tuberculosis or an independent effect of dust. A miner working at a respirable dust intensity of 0.37 mg/m^3 for 30 years would lose on average an additional 208 ml in FVC (95% CI 3, 412) in the absence of other disease, an impact greater than that of silicosis and comparable to that of tuberculosis. Improved dust control on the South African gold mines would reduce the risk of silicosis, tuberculosis and lung function impairment.

What this paper adds

- This is the first study to examine the association between cumulative dust exposure measured gravimetrically and loss of lung function in black gold miners in South Africa.
- It also examined the effect of radiological silicosis and a history of pulmonary tuberculosis on lung function loss controlling for dust exposure.
- We found that silicosis, past or current pulmonary tuberculosis, and respirable dust are all independently associated with appreciable lung function loss in black South African gold miners.
- If the assumption of historical stability of dust exposures is correct, substantial lung function loss in this population of older mineworkers occurred even though they had been exposed to a mean respirable dust concentration below 0.4 mg/m^3 and a mean respirable quartz concentration below the South African mining occupational exposure limit of 0.1 mg/m^3.
- Stricter control of the exposure of underground gold miners to quartz dust and to respirable dust more generally is indicated on a number of health grounds: to prevent silicosis, to reduce the risk of silica related tuberculosis and to prevent dust related lung function loss via other pathways.

The South African gold mining industry is currently experiencing an epidemic of silicosis and tuberculosis among mineworkers.[1–7] This burden is carried particularly by black migrant workers, understood as a socioeconomic population from rural areas of South Africa and neighbouring countries who make up most of the underground workforce. It is likely that the lengthening service of black mine workers after the introduction of labour stabilisation in the 1970s[8 9] has been a major contributor to the high prevalence of silicosis and silica related tuberculosis. The HIV epidemic has further contributed to rising tuberculosis incidence rates, in a multiplicative relationship with silicosis.[4]

Despite this growing burden, prior to the 1990s there was very little study of the consequences of silica dust exposure for the health of black miners.[9] Studies of working miners found silicosis to be associated with lung function impairment, the degree of impairment increasing with the degree of nodulation on the chest radiograph.[10 11] An association of silicosis with emphysema was also found.[12] The association between lung function loss and silicosis (or increasing grades of silicosis) was replicated in two studies of former miners.[1 2] However, only one of the above studies[10] was able to show an association between lung function loss and length of mining service. It was also the only study to show an association of lung function loss with smoking.

No dust measurements were available in any of the above studies, which could therefore not distinguish between silicosis and cumulative dust exposure in the causation of lung function loss. The first study of black South African gold miners attempting to link silica dust exposure measured by modern gravimetric methods to disease outcomes was conducted in 2000/2001 among older working mineworkers.[5] This cross-sectional study revealed a 19.6% silicosis prevalence[5] and a 33% prevalence of past tuberculosis on medical history and/or on the chest radiograph.[6] In both studies associations between disease prevalence and dust, whether measured as respirable dust or respirable quartz (crystalline silica), were observable.

The objectives of this third report were to estimate the effect of respirable dust and respirable quartz exposure on spirometric lung function loss in black gold miners, taking into account smoking, silicosis and tuberculosis. Estimates of the effect of silicosis and tuberculosis on lung function could also be derived and allowed an estimate of the combined effects of dust exposure and disease on lung function loss in this population.

METHODS

Study population

The methods have been described in detail elsewhere.[5] A total of 520 working miners from one gold mine ('gold miners' or 'mineworkers') in the North West Province of South Africa were sequentially enrolled in a cross-sectional study during their annual medical surveillance examinations between November 2000 and March 2001. For sampling purposes, age ≥40 years was used as a proxy for length of service to concentrate the study on longer service workers.

Exposure measurement

Complete mining histories were obtained, using a questionnaire, company personnel data and employment bureau data. This included all mining occupations held by each participant and the period of employment in each occupation. Discrepancies were resolved by re-interviewing the employee. Smoking habits and past chest illnesses including tuberculosis were detailed.

In order to quantify respirable dust and respirable quartz exposures, a separate random sample of 100 underground workers participated in personal full shift gravimetric monitoring over a 5-day period. Gravimetric analysis was carried out on the mine by an occupational hygienist. Data from the government mandated system of dust surveillance were used to augment the research data to cover the occupations not included in the research dust study, and thus to construct a job-exposure matrix in which the mean respirable dust and respirable quartz time weighted average (TWA) concentrations for each occupation were calculated.

Quartz fractions were measured by x-ray diffraction, using a technique which conforms in principle with National Institute for Occupational Safety and Health (NIOSH) 7500, a method approved by the South African Department of Minerals and Energy. Filters were pooled in batches of four or five by occupation prior to being sent for quartz analysis.

The following exposure variables for each miner were then calculated: length of service was the sum of all contract years worked in each occupation; cumulative dust-years and cumulative quartz-years were the length of service in each occupation multiplied by the TWA concentration for respirable dust and respirable quartz respectively (summed over all occupations); and average intensity was cumulative dust-years or cumulative quartz-years divided by the length of service.

Chest radiography

Full size postero-anterior chest radiographs were taken according to International Labour Organization (ILO) specifications, and read by two NIOSH trained readers using the ILO Classification of Chest Radiographs of the Pneumoconioses.[13] Silicosis was defined as a profusion of ≥1/1 on the ILO scale. The readers, who were familiar with the radiological features of tuberculosis, classified tuberculosis as present or absent according to the ILO Classification which provides a single symbol for tuberculosis. Typical features of inactive tuberculosis include asymmetrical linear or nodular fibrosis, particularly in the upper zones, bronchiectasis and unilateral diffuse pleural thickening. Cavitation, soft infiltrates, lymphadenopathy, pleural effusion, a miliary pattern or bronchopneumonic consolidation suggest active tuberculosis, although activity can only be established bacteriologically. The readings of the two readers were analysed separately.

Lung function testing

Lung function testing was conducted at the mine's Occupational Health Centre by trained staff. Height and weight were measured without shoes. Calibration was carried out prior to each new session. Forced expiratory volume in 1 s (FEV_1) and forced vital capacity (FVC) were measured in the standing position without a nose clip, using a pneumotachograph (Masterscope CT, Jaeger, Germany). American Thoracic Society criteria[14] were used for quality control. The prediction equations were those estimated by Louw[15] based on a 1988 study of black South African men engaged in non-dusty occupations in Johannesburg. 'Excess loss' was defined as the difference between the predicted and observed values of FEV_1 and FVC, and thus intrinsically adjusted for age and height. A positive sign for this variable denotes an observed volume that is less than predicted for that age and height, and a negative sign an observed volume that exceeds the predicted.

Statistical analysis

The data were analysed using Stata 10 (Intercooled Stata 10 for Windows). Outcome variables were FEV_1 and FVC excess loss as defined above. Silicosis was regarded as a potential mediator of the effect of silica dust on lung function, that is as lying on the causal pathway, and tuberculosis as a potential mediator or confounder. Smoking history (classified as never, ex- and current, and measured also as pack-years) was treated as a potential confounder. Tuberculosis was defined variously as a history of tuberculosis (previous or current), radiographic tuberculosis (any features of active or inactive tuberculosis on the chest radiograph) or 'any' tuberculosis (history and/or radiographic appearance).

Linear regression was used to estimate the effect of exposure on lung function excess loss. The total or 'overall' effect of the exposure on outcome can be decomposed into the sum of 'direct' (unmediated) and 'indirect' (mediated) effects. Multivariate regression analysis was used to estimate the overall effect of exposure as well as the direct effect, that is the effect not mediated through silicosis and/or tuberculosis. The fit of the linear regression models was assessed by examination of residuals, in particular for indications of non-linearity or heteroscedasticity.

Ethics approval was obtained from the Research Ethics Committee of the Health Sciences Faculty of the University of Witwatersrand and from the company health services' Medical Research Ethics Committee. Written informed consent was obtained from each subject. All miners with abnormalities, including abnormal lung function tests detected during the annual fitness examination, are seen by the medical officer at the mine's Occupational Health Centre and referred for further investigation and management if required.

RESULTS

Descriptive characteristics

Table 1 presents the occupational and exposure characteristics of the 520 participants. They were aged between 37 and 60 years (mean 46.7 years). The range of gold mining service was 6.3 to

34.5 years (mean 21.8 years). A total of 85 different occupations were represented in the sample, consisting of both underground and surface jobs. The median number of jobs held was five (range 1–16). The range of average intensity of respirable dust was 0.0–0.7 mg/m^3 and of respirable quartz 0.00–0.09 mg/m^3.

Both the observed mean FEV_1 and mean FVC (measured in ml) were greater than the predicted means, yielding a 'negative' mean excess loss in each case. The mean FEV_1/FVC ratio was 80%, equal to the predicted value.

Table 2 summarises the medical and smoking features of the sample subjects. Of the miners, 28.8% were current smokers and 22.5% ex-smokers. The median number of cigarettes (including hand-rolled) smoked daily was 5.3 (range 0–20) and median pack-years 4.9 (mean 6.2, range 0–35) (not shown), indicating low consumption rates. There was a report of previous tuberculosis in 19.4%, while nine (1.7%) were currently on tuberculosis therapy, giving a proportion of 21.1% with a history of past or current pulmonary tuberculosis. Signs of pulmonary tuberculosis (irrespective of medical history) were read in 27.8% of the radiographs by reader 1 and in 17.5% by reader 2.

Agreement between the two readers was examined. At a profusion cut-point on the ILO Classification of 1/1 and above versus 1/0 and below for silicosis, concordance was 93.5% and κ 0.79 (95% CI 0.70 to 0.88), signifying excellent agreement. The equivalent agreement for any tuberculosis on the chest radiograph was 86.7% and κ 0.62 (95% CI 0.55 to 0.69). Since regression coefficients differed little whether the radiographic variables were derived from reader 1 or reader 2, the findings of reader 1 for silicosis and tuberculosis were used in the analyses that follow.

Bivariate analysis

Regression diagnostics did not indicate any violations of the linear regression assumptions, in particular linearity and homoscedasticity. Bivariate associations between FEV_1 and FVC excess loss and exposure measures are shown in table 3. These estimates represent the crude overall effect of each exposure on mean excess loss, without consideration of the mediating diseases, silicosis and tuberculosis, or the potential confounding effect of tuberculosis or smoking. The linear regression coefficient represents the estimated increase (in ml) in mean FEV_1 (or FVC) excess loss per unit increment in the exposure variable. For example, it was estimated that mean FEV_1 excess loss increased by 35.7 ml for every 0.01 mg/m^3 increase in average respirable quartz. Similarly, there was an estimated 156 ml increase in mean FEV_1 excess loss for every 1 mg-yr/m^3 increase in cumulative quartz exposure (accumulated, for example, as 10 years of exposure to a mean respirable quartz concentration of 0.1 mg/m^3). The effects of the exposure variables on FVC in the regression were similar to those on FEV_1.

Table 1 Age, exposure and spirometric characteristics in working gold miners (n=520)

Exposure variable	Mean	SD	Median	Range
Age (years)	46.7	4.4	46.1	37.1–59.9
Number of jobs	5.3	2.6	5	1–16
Length of service (years)	21.8	5.3	21.9	6.3–34.5
Quartz fraction (%)*	14.0	1.5	14.1	0–16.5
Cumulative respirable dust (mg-yr/m^3)	8.2	2.90	7.95	0–22.68
Cumulative respirable quartz (mg-yr/m^3)	1.15	0.44	1.13	0–3.08
Average intensity respirable dust (mg/m^3)	0.375	0.098	0.367	0–0.706
Average intensity respirable quartz (mg/m^3)	0.053	0.016	0.051	0–0.096
Measured FEV_1 (ml)	3256	632	3230	1260–5230
FEV_1 excess loss (ml)†	−152	572	−168	−1644 to +1689
Measured FVC (ml)	4069	704	3995	1350–6400
FVC excess loss (ml)†	−159	618	−129	−2030 to +2378

*Mean percentage quartz derived for each individual by dividing cumulative respirable dust exposure by cumulative respirable quartz exposure.
†Inherently adjusted for age and height. Minus sign denotes observed>predicted.
FEV_1, forced expiratory volume in 1 s; FVC, forced vital capacity.

Table 2 Tuberculosis history, radiological findings and smoking characteristics in working gold miners (n=520)

	Present	%	95% CI
Past TB (reported)	101	19.4	16.0 to 22.8
Current TB	9	1.7	0.8 to 3.3
Reader 1 (n=515)*			
TB	143	27.8	23.9 to 31.9
Silicosis	93	18.1	14.8 to 21.7
TB+silicosis	28	5.4	3.6 to 7.8
PMF	4	0.8	0.2 to 2.0
Reader 2 (n=513)*			
TB	90	17.5	14.4 to 21.1
Silicosis	102	19.9	16.5 to 23.6
TB+silicosis	24	4.5	3.0 to 6.9
PMF	5	1.0	0.3 to 2.3
TB by any measure†	183	35.2	31.1 to 39.3
Ever smokers	267	51.3	47.0 to 55.7
Current smokers	150	28.8	24.9 to 32.8
Ex-smokers	117	22.5	18.9 to 26.1

*Films readable for pneumoconiosis.
†TB ever (reported), or active or inactive TB read on the chest radiograph by either reader.
PMF, progressive massive fibrosis; TB, pulmonary tuberculosis.

The estimated mean difference in excess loss comparing those for whom each mediating/confounding variable was present with those for whom it was absent, is also shown in table 3. The presence of either silicosis or pulmonary tuberculosis (any definition) was associated with a substantial increase in mean excess loss in both FEV_1 and FVC. For example, it was estimated that the mean FEV_1 excess loss was 259.3 ml greater in subjects with silicosis compared to those without. The effect of both of these diseases on FEV_1 was more marked than the effect on FVC. By contrast, smoking was weakly, if at all, associated with lung function excess loss. Considering smoking measured as pack-years did not alter this finding.

Multivariate analysis

Using separate multivariate regression models, the effects of a number of different exposure metrics were estimated (table 4). Length of service was considered in a model of its own and in a model with average intensity of exposure. The multivariate analysis for each exposure measure included both silicosis and tuberculosis.

Tuberculosis and silicosis remained significant predictors of FEV_1 excess loss, and tuberculosis of FVC excess loss. There was no significant interaction between silicosis and tuberculosis (analysis not shown), so that their effects on mean excess loss were additive.

To test for possible residual confounding by smoking and height, the models were also fitted with the addition of these variables. There was no meaningful change in the parameter estimates and associated confidence intervals for the exposure variables.

If silicosis and tuberculosis are regarded as mediators, then dust exposure coefficients in the multivariate analysis represent estimates of the direct effect of exposure not mediated by these

Table 3 Bivariate associations of exposure measures with FEV_1 and FVC excess loss* (n=520)

Exposure variable	FEV_1 excess loss (ml)		FVC excess loss (ml)	
	Linear regression coefficient	95% CI	Linear regression coefficient	95% CI
Length of service (per year)	7.6	−1.7 to 16.9	3.3	−6.8 to 13.4
Cumulative respirable dust (per mg-yr/m^3)	25.7	8.8 to 42.5	23.6	5.3 to 41.8
Cumulative respirable quartz (per mg-yr/m^3)	156.0	44.5 to 267.5	150.0	29.4 to 270.5
Average respirable dust (per 0.01 mg/m^3)†	6.9	1.8 to 11.9	8.4	3.0 to 13.8
Average respirable quartz (per 0.01 mg/m^3)†	35.7	4.8 to 66.6	47.0	13.8 to 80.3
Silicosis (reader 1)	259.3	132.9 to 385.7	160.5	22.3 to 298.8
Ever smoker (vs never)	65.4	−33.2 to 163.9	16.6	−89.9 to 123.2
Ex-smoker (vs never)	88.3	−38.4 to 215.0	52.3	−86.3 to 191.8
Current smoker (vs never)	47.5	−64.3 to 159.2	11.1	−133.0 to 110.7
TB on radiograph (reader 1)	349.0	242.7 to 455.3	258.3	143.1 to 373.4
TB history (past or current)	296.6	174.6 to 418.7	212.1	79.7 to 345.4
TB (any definition)	270.0	169.2 to 370.5	172.3	61.7 to 282.7

*Inherently adjusted for age and height.
†Unit increment of 0.01 rather than 0.001 to enable coefficients to be expressed as integers.
FEV_1, forced expiratory volume in 1 s; FVC, forced vital capacity; TB, pulmonary tuberculosis.

diseases. In the case of most of the coefficients compared to the unadjusted analysis (table 3), about a third of the overall effect of exposure appeared to be mediated by tuberculosis and silicosis. For example, the estimated effect of cumulative quartz exposure on FEV_1 excess loss was reduced from a mean excess loss of 156 ml per mg-yr/m^3 to 95.6 ml per mg-yr/m^3 with a 95% CI that no longer excluded a zero effect. Cumulative dust, average dust and average quartz retained direct effects on FVC excess loss with confidence intervals which excluded a zero effect, although with lower limits close to zero.

Regression coefficients may give a misleading picture of the relative strength of the effect of exposure metrics which have different units or even of the same exposure metric with widely differing ranges.[6] The coefficients for the dust and quartz metrics were thus expressed in IQR (interquartile range) units (table 4). On this scale, there was no difference in the strength of effect between the cumulative dust and quartz metrics, while average dust intensity showed a stronger effect per IQR than average quartz intensity.

These findings can be extrapolated to exposure over a working lifetime. An estimated mean excess loss of 16.2 ml in FEV_1 for each 1 mg-yr/m^3 of cumulative dust implies that the average miner without silicosis or tuberculosis working for 30 years at the median dust intensity of 0.37 mg/m^3 (cumulative dust exposure 11.1 mg-yrs/m^3) would lose an additional 180 ml (95% CI −3 to 362). The equivalent loss in FVC would be 208 ml (95% CI 3 to 412). If in addition the miner developed silicosis (mean excess FEV_1 loss 224 ml as per table 4) and tuberculosis (mean excess FEV_1 loss 347 ml), his combined average FEV_1 excess loss, that is over and above ageing, would be 751 ml (95% CI 535 to 967). The equivalent estimate for FVC is somewhat less at 595 ml (95% CI 354 to 837).

Silicosis grade and lung function loss

In order to take radiological severity of silicosis into account, figure 1 demonstrates the gradient in excess FEV_1 loss by increasing profusion on the ILO major scale for silicosis alone and for silicosis plus radiological tuberculosis. The plotted values for average excess loss in each grade are derived from a linear regression model for FEV_1 excess loss including only dummy variables for silicosis grade and tuberculosis but no dust exposure variables. A monotonic increase across silicosis grades is evident with and without tuberculosis. Because these working miners with neither silicosis nor tuberculosis have an average FEV_1

Table 4 Associations in multivariate analysis of FEV_1 and FVC excess loss* with exposure variables in models that include silicosis and tuberculosis (n=520)

Exposure variable†	FEV_1 excess loss (ml)		FVC excess loss (ml)	
	Linear regression coefficient	95% CI	Linear regression coefficient	95% CI
Length of service (per year)	3.0	−6.1 to 12.2	0.7	−9.5 to 11.0
Cumulative respirable dust (per mg-yr/m^3)	16.2	−0.3 to 32.6	18.7	0.3 to 37.1
(per IQR)	59.2	−1.2 to 119.2	68.2	1.3 to 135.4
Cumulative respirable quartz (per mg-yr/m^3)	95.6	−13.0 to 204.2	118.6	−2.6 to 239.9
(per IQR)	55.1	−7.2 to 117.6	68.3	−1.5 to 138.2
Average respirable dust (per 0.01 mg/m^3)‡	4.8	0 to 9.6	7.2	1.8 to 12.5
(per IQR)	69.2	0.0 to 138.4	103.1	25.9 to 180.2
Average respirable quartz (per 0.01 mg/m^3)‡	24.3	−5.2 to 53.9	40.1	7.1 to 73.1
(per IQR)	53.0	−11.4 to 117.5	87.4	15.6 to 159.2
Silicosis (reader 1)§	224.1	104.3 to 347.7	123.6	−14.5 to 261.9
TB (radiological, reader 1)§	347.4	242.7 to 452.1	264.3	147.4 to 381.3

*Inherently adjusted for age and height.
†Separate model estimated for each exposure metric.
‡Adjusted for length of service as well. Unit increment of 0.01 rather than 0.001 to enable coefficients to be expressed as integers.
§As estimated in the model with cumulative dust exposure.
FEV_1, forced expiratory volume in 1 s; FVC, forced vital capacity; IQR, interquartile range; TB, pulmonary tuberculosis.

greater than predicted, positive excess loss (ie, observed< predicted) becomes apparent only in ILO silicosis category 3. Among those with both silicosis and tuberculosis, excess loss is apparent at all grades of silicosis.

DISCUSSION

This sample of older working miners were found to have on average better lung function than a reference population[15] drawn from non-dust exposed workers in Johannesburg. This may reflect a healthy worker 'survivor' effect through which workers with respiratory disorders are selected out of the working population over time. Irrespective of this effect, increasing exposure to both respirable dust and respirable quartz was associated with increasing excess loss in both FEV_1 and FVC. Three interrelated sources of lung function loss, over and above ageing, were evident in this analysis: silicosis, past or current pulmonary tuberculosis, and dust exposure.

Smoking played no role in lung function loss in this group. This is consistent with previous studies of black miners that failed to show any association between smoking and lung function loss.[1 2 11] The likely reason for this is a low daily consumption of cigarettes. While 51% of this group had ever smoked, only 28% were current smokers. The median number of cigarettes smoked daily was only 5.3 and median pack-years 4.9. A study of over 25 000 platinum miners, who are likely to be similar to gold miners with regard to smoking, found that 87% of current smokers smoked fewer than 10 cigarettes daily,[16] with the average being five cigarettes daily.

The clear silicosis effect on lung function after controlling for dust exposure contrasts with earlier findings in studies of white gold miners,[17 18] in which silicosis was not associated with spirometric lung function loss after dust exposure was accounted for. The results of the current study suggest that the repeated finding of an association of silicosis with lung function loss in the mainly black gold mining population[1 2 10 11] is a feature of the disease and not due purely to unmeasured dust exposure operating via other pathways. A recent review[19] has argued that emphysema is a potential confounder of the relationship between silicosis and lung function loss. In an autopsy study of white miners, no association between silicosis and emphysema was found.[20] In contrast, a later study of black working miners using computerised tomography showed an increasing prevalence of emphysema with increasing grades of silicosis.[12] Emphysema was not measured in the study reported here and its role could therefore not be tested.

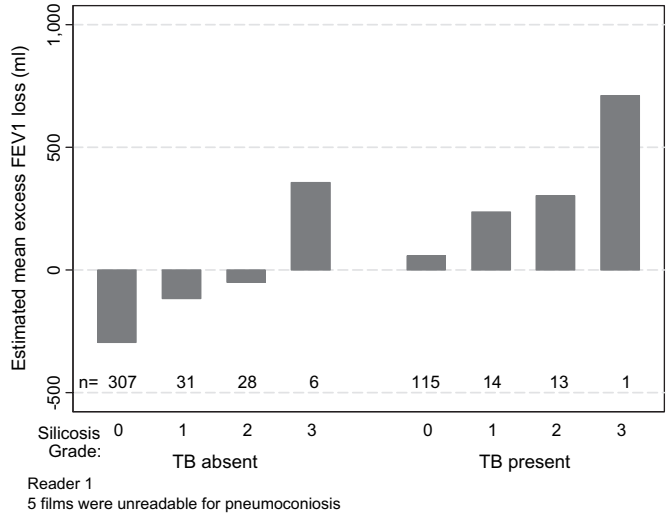

Figure 1 Excess FEV_1 loss by major International Labour Organization (ILO) category of silicosis with and without tuberculosis (n=515).

The study also adds to the evidence that pulmonary tuberculosis is associated with substantial lung function loss in gold miners, which is greater for FEV_1 than for FVC.[21] This effect is at least additive with that of silicosis and cumulative dust exposure.

Dependence on participant recall of tuberculosis is a limitation of the study. As the clinical pictures of pulmonary tuberculosis and non-tuberculous mycobacterial disease are indistinguishable, it is possible that approximately 10% of the disease recalled as tuberculosis by the participants was in fact non-tuberculous mycobacterial disease.[22] However, given the similarity of the two diseases, such misclassification is unlikely to affect the overall finding regarding the effect of tuberculosis on lung function. Other respiratory diseases are unlikely to be confused with tuberculosis as the prolonged chemotherapy associated with tuberculosis is well known among miners.

Another limitation of the study is that HIV infection, with a prevalence approximately 23–27% among gold miners,[7 23 24] was not measured. However, while HIV infection increases the risk of tuberculosis and of other respiratory disease, the net effect of HIV infection on lung function in a sample of miners fit enough to remain at work is unpredictable. In one study of working miners, HIV infection did not influence the association between tuberculosis and lung function loss.[21]

Although the effect of dust alone is thus clinically modest for the average miner, there are number of reasons why the independent impact on lung function estimated for dust can be regarded only as a minimum. A healthy worker selection effect, including that due to tuberculosis, has been mentioned above. Further, since miners who develop silicotic fibrosis may also be more susceptible to other effects of silica, for example mineral dust disease or emphysema,[25] than miners without silicosis, regression analysis cannot truly partition lung function loss into that due to dust and that due to fibrosis.

The impact of silicosis and pulmonary tuberculosis on FEV_1 excess loss was greater than that on FVC excess loss, indicating a tendency to increased obstruction with these diseases. In contrast, the effect of dust exposure, whether as dust or quartz, was greater on FVC loss than on FEV_1 loss. This is somewhat surprising since if the dust effect were being mediated via mineral dust airways disease[25] and/or emphysema,[12 20 26] the obstructive effect would be expected to be the stronger. A possible explanation is that miners with obstructive impairment are more likely to be selected out of the workforce because of the association between silicosis and tuberculosis and obstructive loss as discussed above.

This study cannot capture the long-term impact of dust related disease on former mineworkers, among whom the burden may be higher than in the population studied. Former mineworkers remain at risk of silicosis[3 27, 28] and of associated tuberculosis[3] despite ceasing dust exposure. A study of former migrant mineworkers,[1] with shorter mean service length than in this study but with 16 years on average since leaving the industry, found a considerably higher prevalence of airflow obstruction, compatible with a generally higher cumulative burden of lung function impairment among former miners than among active miners.

This is the first study of black gold miners to make use of dust measurements and the first study of any gold mining population

in South Africa to use directly obtained gravimetric exposure measurements. Despite the miners in this sample apparently having worked at average respirable quartz intensities below the South African mining occupational exposure limit of 0.1 mg/m^3, an effect of respirable dust and to a lesser extent respirable quartz on lung function loss could be discerned. This adds to similar findings on the lack of protectiveness of this exposure limit against silicosis or tuberculosis.[5 6 28] As discussed in the previous report on silicosis,[5] this inference depends on the assumption that current or recent dust concentrations are a reasonable proxy for dust concentrations experienced in the same jobs over the previous 6–35 years, and that the calculated quartz concentrations are similarly representative.

Some dust data were available from this mine for the period 1978–1996 which allowed this assumption to be tested (te Water Naude J, Myers J. Trends in dust levels at a gold mine near Orkney in the North West province. Unpublished report, 2003. Available from the authors). Particle count measurements taken with a konimeter during the period 1978–1988 show an upward trend. Gravimetric measurements available from 1992 to 1996 also reflect slightly rising median respirable dust concentrations. Respirable quartz concentrations were all near or below the occupational exposure limit of 0.1 mg/m^3 between 1992 and 1996 and thus compatible with the concentrations derived in this study in 2000/1. Allowing for uncertainties about historical dust counting and quartz calculations, there is nothing to contradict the finding by a government commission in 1995 of essentially static dust concentrations in the gold mining industry over the previous five decades.[29]

In conclusion, this study has demonstrated appreciable loss of lung function attributable to dust exposure in working South African gold miners, mediated via silicosis, pulmonary tuberculosis and/or an independent dust effect. Respirable dust was a slightly better predictor of lung function loss than respirable quartz. Inaccuracies in attributing quartz fractions to individual jobs, for example as a result of pooling of dust specimens, are likely to have resulted in greater misclassification of respirable quartz as an exposure metric with attendant weakening of any associations. Alternatively, respirable dust rather than the respirable silica fraction may be the toxicologically relevant metric for lung function loss.

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Competing interests GJC was employed by AngloGold Ashanti during the conduct of this study. RIE and JEM have written expert reports for use in silicosis litigation.

Ethics approval This study was conducted with the approval of the Research Ethics Committee of the Health Sciences Faculty of the University of Witwatersrand and the Medical Research Ethics Committee of Anglogold Health Services.

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