Paper II

Variability of Exposure and Estimation of Cumulative Exposure in a Manually Operated Coal Mine

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This study aims at estimating variability in exposure to respirable dust and assessing whether the *a priori* grouping by job team is appropriate for an exposure–response study on respiratory effects among workers in a manually operated coal mine in Tanzania. Furthermore, estimated exposure levels were used to calculate cumulative exposure. Full-shift personal respirable dust samples ($n = 204$) were collected from 141 randomly chosen workers at underground and surface work sites. The geometric mean exposure for respirable dust varied from 0.07 mg m^{-3} for office workers to 1.96 mg m^{-3} for the development team. The analogous range of respirable quartz exposure was 0.006–0.073 mg m^{-3}. Variance components were estimated using random effect models. For most job teams the within-worker variance component was considerably higher than the between-worker variance component. For respirable dust the estimated attenuation of the linear exposure–response relationship was low (5.9%) when grouping by job team. Grouping by job team was considered appropriate for studying the association between current dust exposure and respiratory effects. Based on the estimated worker-specific mean exposure in the job teams, the arithmetic mean cumulative exposure for the 299 workers who participated in the epidemiological part of the study was 38.1 mg˙ yr m^{-3} for respirable dust and 2.0 mg˙ yr m^{-3} for quartz.

Keywords: coal mining; cumulative exposure; exposure variability; respirable dust; quartz

INTRODUCTION

Quantitative exposure assessment in coal mining was pioneered by Oldham (1953) in England and has successfully been used in other studies (Werner and Attfield, 2000; Heederik and Attfield, 2000). There is an increasing trend towards studying quantitative exposure–response relationships for occupational health outcomes (Tielemans *et al.*, 1998; Loomis and Kromhout, 2004). The use of variance components of exposure data has been proposed for establishing appropriate ways of grouping workers for epidemiological studies (Kromhout and Heederik, 1995; Kromhout *et al.*, 1996; van Tongeren *et al.*, 1997). The efficiency of grouping schemes has been based on high contrast in exposure between

subgroups (Kromhout and Heederik, 1995), low attenuation and inflated standard error of the theoretical linear exposure–response slope (van Tongeren *et al.*, 1997; Tielemans *et al.*, 1998; Mwaiselage *et al.*, 2005) and decreased between-worker variance by grouping of workers (Tjoe *et al.*, 2004). Attenuation is the bias in the estimated linear exposure–response relationship towards zero and can be caused by, amongst others, non-differential misclassification of exposure. Attenuation of exposure can be a serious problem in studies where time varying exposure is estimated for each individual in the study (van Tongeren *et al.*, 1997). When the exposure is highly variable from day to day and only a limited number of measurements are available, severe attenuation of the exposure–response slope can occur (van Tongeren *et al.*, 1997; Tielemans *et al.*, 1998, Mwaiselage *et al.*, 2005). This problem can be solved by increasing the number of repeated measurements on the same individual, although this is often not an option

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due to limited resources available. Occupational epidemiological studies usually apply a grouping approach for exposure estimates (Kromhout *et al.*, 1993; Rappaport *et al.*, 1995). In this approach, workers are grouped based on task, location and other factors which are predictors of their exposure, and a sample of workers is selected for exposure monitoring. Subsequently, the mean of the results is applied to the whole group. It has been suggested that attenuation of exposure when applying a grouping strategy is reduced, although this strategy suffers from increased standard errors of the exposure–response slope (Loomis and Kromhout, 2004).

Grouping schemes for coal miners have been recognized and used in mechanized mining for many years (Dodgson *et al.*, 1970; Heederik and Miller, 1988; Werner and Attfield, 2000; Heederik and Attfield, 2000; Kizil and Donoghue, 2002). However, information is lacking on the variability in dust exposure and on grouping scheme efficiency in manually operated coal mines. Such mines are numerous worldwide, particularly in developing countries. We have previously reported high exposures to respirable dust and quartz among underground workers in a labour-intensive coal mine in Tanzania (Mamuya *et al.*, 2006).

The aim of this study was to estimate the variance components of exposure to respirable dust and quartz and thereby assess whether the *a priori* grouping by job team is appropriate for studying the association between cumulative dust and quartz exposure and chronic respiratory symptoms and changes in lung function among the workers in a labour-intensive coal mine. The estimated worker-specific mean exposure levels for the workers in the job teams were used to calculate the cumulative exposure of individual workers, which is considered a relevant measure of exposure in studies of chronic respiratory effects (Rappaport, 1991).

METHODS

Settings

The study was conducted at the coal mine in Mbeya region, Tanzania. The mine was started in 1988 and operates the Kiwira collieries. The annual coal production is about 150 000 tonnes, and 556 surface and underground workers are employed.

The underground workers in Kiwira include 41 in the development team, 75 in the mining team, 37 in underground transport and 34 in underground maintenance. The main work processes of the underground development workers are pneumatic drilling, blasting and lashing of the hard rock materials to create roadways. The mine team is located at the coalface and is involved in drilling, blasting and lashing of coal. The underground maintenance team maintains various utilities and equipment, while the underground

transport team operates the locomotives and maintains the rail lines.

Surface workers in Kiwira comprise 41 workers in the washing plant, 37 in boiler and turbine, 27 in ash and cinders, 129 in administration and 126 workers in carpentry, masonry, garage, foundry, welding, machine workshop and surveillance. In the washing plant, coal is ground, screened and washed under pressurized water to remove the sulphur content. Separation of unwanted particles is the last process. There are operators for all these processes. The power plant uses the processed coal to produce electric power for use at the site and for sale to the national grid. Workers in the power plant are mainly located in the boiler and turbine or in the ash and cinders. The boiler operators are responsible for controlling coal and water by a control panel. In the turbines section, the operators are responsible for regulating steam and pressure in the turbines. Attendants in ash and cinders are responsible for feeding coal to the boiler conveyor belt and for removing ash and cinders remnants from the boiler to the disposal area. They push trolleys with fine ash to the damping area.

In the present study job team was the *a priori* grouping scheme by which the mine management classified workers into eight groups: development, mine, underground maintenance, underground transport, washing plant, boilers and turbine, ash and cinders, and office.

Dust-sampling strategy

Personal dust exposure was measured in two periods: June–August 2003 (period 1) and July–August 2004 (period 2). These periods were chosen due to practical limits for fieldwork at the University of Bergen. Sampling was planned for both surface (ash and cinder, washing plant, boiler and turbine, office) and underground workers (development, mining, underground transport and underground maintenance). In the first period of sampling, we had no information on the exposure of the coal miners. Thus, dust samples were allocated into different groups of workers using the method described by Leidel *et al.*, (1977) as a guideline. A total of 110 filter cassettes for respirable dust were available for dust sampling. The numbers of samples allocated were 17 from development, 29 from the mining team, 13 from underground transport, 13 from the wash plant, 10 from boiler and turbine and 12 from ash and cinders. Only 14 samples were taken from the groups presumed to have low exposure: 5 from underground maintenance and 9 from office. Two filters had similar laboratory identification and were omitted. The workers selected for personal dust sampling were randomly selected from the list of workers. In the second sampling period, reselection of workers from the first sampling period was possible, and the number of measurements allocated was based on the

exposure concentrations obtained from the first period, which were aggregated into low, medium and high exposure (Mamuya et al., 2004). Due to a higher expected variability for the most exposed workers the available 100 samples were planned to be distributed to the low-, medium- and high-exposed groups in proportions of 1:3:5 as indicated by Loomis et al. (1994). The low-exposure group comprised office, underground transport and boiler and turbine; the medium-exposure group comprised the mining team, underground maintenance, wash plant and ash and cinders; and the development team constituted the high-exposure group. For practical reasons, five workers declined to participate, and due to the time limit for conducting the study five samples were not taken. The actual number of samples taken was 41 in development, 17 in the mining team, 10 in underground maintenance, 2 in underground transport, 10 in washing plant, 10 in ash and cinders, 4 in boiler and turbine, and 2 in office. Totally 204 respirable dust samples were taken from 141 workers. The number of samples per worker ranged from 1 to 3.

Dust sampling and analysis

Personal dust sampling was performed during the day shift for both periods, which normally lasted 5–10 h. Five full-shift samples were taken on each monitoring day. Personal respirable dust was collected on 37 mm cellulose acetate filters (pore size 0.8 μm) placed in a 37 mm SKC conductive plastic cyclone (Cat No.225-69), using an SKC Sidekick pump (model 224-50) with a flow rate of 2.2 l min^{-1}. A rotameter was used to adjust the flow. The cyclone was clipped to the worker's collar, allowing it to hang freely and collect dust in the breathing zone.

The respirable dust samples were quantified by gravimetric analysis using a Mettler AT 261 delta range with a readability of 0.01 mg at the X-Lab laboratory in Bergen, Norway. The limit of detection (0.01 mg m^{-3}) was calculated as the readability of the Mettler instrument divided by the total air volume passing through the filter during a sampling period of 8 h. The respirable dust samples were analysed for quartz by X-ray diffraction on a silver membrane filter using NIOSH method 7500 at SGAB Analytica Laboratory, Luleå, Sweden. In the first sampling period, all respirable dust samples from the development ($n = 17$) and mining teams ($n = 29$) and a random selection of samples from underground transport ($n = 6$) and maintenance ($n = 4$) were analysed for quartz. Two measurements from the development team ($n = 1$) and the mining team ($n = 1$) were not analysed as they accidentally were not sent for laboratory analysis. In the second period, all dust measurements were analysed for quartz. Respirable dust samples were analysed for quartz by X-ray diffraction on a silver membrane filter using

NIOSH method 7500 at SGAB Analytica Laboratory, Luleå, Sweden. The limit of detection (LOD) was 0.005 mg m^{-3}. X-Lab in Bergen passed the intercalibration test of the Norwegian Institute of Occupational Health in Oslo, and SGAB Analytica Laboratory passed the intercalibration test of the Swedish Board for Accreditation and Conformity Assessment (SWEDAC).

Preparation for epidemiological study

From the total list of about 556 workers supplied by the Kiwira coal mine management, exclusions from the study were made for 220 workers including managers, assistant managers, heads of section due to their high social economic status; temporary workers who are not reliable for further epidemiological studies, and surface workers in carpentry, masonry, garage, foundry, welding, machine workshop and surveying due to other types of exposures which might confound our study. The remaining 336 workers from Kiwira were invited to participate in the study; 18 did not attend, thus leaving a study population of 318 workers: 299 men and 15 women and 4 diseased. Two workers with bronchial asthma and two with tuberculosis and women were excluded before statistical analysis. The 299 workers were from development (47), mine team (78), underground maintenance (34), underground transport (30), washing plant (23), boiler and turbine (17), ash and cinders (21) and office (49). All these workers were asked to provide their job history, including the number of years worked in the respective job team.

Statistical analysis

The exposure data were close to log-normally distributed and were log-transformed for statistical analysis (Esmen and Hammad, 1977; Lyles et al., 1997). Values below the limit of detection for respirable dust ($n = 1$) and quartz ($n = 37$) were estimated by dividing the limit of detection value by 2 (Hornung and Reed, 1990). A one-way random-effect model was used to estimate the between-worker ($_{bw}S^2$) and the within-worker ($_{ww}S^2$) variance components (Kromhout and Heederik, 1995). The worker identity was treated as a random effect. The ratio between the 97.5th and 2.5th percentiles of the between-worker and within-worker distributions of exposure, respectively, provides information about the ranges of exposure experienced between workers and from day-to-day (within workers) and were estimated as described by Rappaport (1991):

$$_{bw}R_{0.95} = \exp(3.92 *_{bw}S)$$

and

$$_{ww}R_{0.95} = \exp(3.92 *_{ww}S)$$

For respirable dust and quartz exposure a two-way nested random-effect model was used to estimate the

variance components between groups $(_{bg}S^2)$, within groups $(_{wg}S^2)$ and within workers $(_{ww}S^2)$ (Kromhout and Heederik, 1995). In this model, the worker groups and the worker identity were treated as random effects. The attenuation and standard error of the observed exposure–response slope for the *a priori* grouping by job team were assessed by using the variance components from the two-way random-effect model to calculate the ratio of the observed to the true regression coefficient of the exposure–response curve ($\beta*/\beta$) according to van Tongeren *et al.* (1997) and Tielemans *et al.* (1998). In these estimations the true regression coefficient and the variance of the response variable were set as -0.1 and 0.15, respectively (van Tongeren *et al.*, 1997), the number of repeated measurements per worker was rounded up from 1.5 to 2, and the number of workers in each subgroup was entered as the total number of workers divided by the number of subgroups in the *a priori* grouping scheme. Restricted maximum likelihood was used for all parameters due to the unbalanced nature of the data (Searle *et al.*, 1992).

The estimated worker-specific mean exposure in job team $h(\mu_{x,h(i)})$ was calculated as described by Rappaport *et al.* (1999):

$$\mu_{x,h(i)} = \exp\left(\mu_{x,h(i)} + 0.5 *_{ww}S^2\right),$$

where $\mu_{y,h(i)}$ represents the fixed mean (logged) exposure for job team h and $_{ww}S^2$ is the within-worker variance component.

The individual cumulative exposure values (CE$_i$) to respirable dust or quartz (mg·yr m^{-3}) for the 299 workers who participated in a subsequent study on respiratory health effects were calculated analogously to Seixas *et al.* (1991, 1993):

$$\mathrm{CE}_i = \sum \left(\mu_{x,h(i)}\right)\left(t_{h(i)}\right),$$

where CE$_i$ = estimated cumulative respirable dust or quartz in mg·yr m^{-3} for worker i. $t_{h(i)}$ = number of years worker i has spent in job team h. SPSS version 12.0 software was used in all statistical analysis.

RESULTS

Figure 1 and Table 1 present the distribution of personal exposure to respirable dust based on the *a priori* job teams. The geometric mean exposure values to respirable dust and quartz for underground workers, including the development team (1.80 and 0.073 mg m^{-3}, respectively), mine team (0.47 and 0.013 mg m^{-3}), transport team (0.14 and 0.006 mg m^{-3}) and maintenance team (0.58 and 0.016 mg m^{-3}) have been presented previously (Mamuya *et al.*, 2006). The corresponding exposure values

for the surface teams, comprising the workers in the washing plant (geometric mean 0.41 and 0.011 mg m^{-3}), boiler and turbine (0.31 and 0.020 mg m^{-3}), ash and cinder (0.73 and 0.020 mg m^{-3}) and office (0.07 and 0.006 mg m^{-3}), generally had lower total variability ($_tS^2 = 1.22$) than those of the underground teams ($_tS^2 = 3.50$). The within-worker variance component was considerably higher than the between-worker variance component for most job teams (Table 1). The results indicate that the ratios of the 97.5th and 2.5th percentiles of the between-worker distribution of respirable dust exposure were relatively low, varying between 1.0 and 22.5 in the 8 job teams, while the analogous within-worker distribution varied between 2.2 and 3902 (Table 1). The within-worker variance component was particularly large for the development and the underground maintenance teams, indicating a large day-to-day variation in exposure in these teams. Whereas the between-worker variance components for respirable dust appeared to be relatively similar in the job teams, the day-to-day variance components differed across the teams.

However, when analysed by the two-way random model, which assumes common variances across the groups, the job team grouping had between-group, within-group and within-worker variance components for respirable dust of 0.89, 0.08 and 1.96, respectively. For quartz the analogous variance components were 0.47, 0.0 and 3.04. Based on these data the observed regression coefficient ($\beta*$) was estimated to be 0.0943 for respirable dust and 0.0823, for quartz with standard errors of 0.043 and 0.061, respectively. The estimated $\beta*$-values indicated attenuations of the exposure response curve of 5.7% for respirable dust and 17.7% for quartz.

The estimated worker-specific mean exposure ($\mu_{x,h(i)}$) for respirable dust ranged from 0.07 mg m^{-3} for office workers to 18.17 mg m^{-3} for hard rock and from 0.007 mg m^{-3} to 0.889 mg m^{-3} for quartz (Table 1). The number of years of employment for the 299 workers who participated in the epidemiological part of the study in the mine ranged from 0.3 to 34 years, with an arithmetic mean of 10.2 years. The mean age of these workers was 37.0 years (range 20.5–57.6 years). Based on the worker-specific mean exposure ($\mu_{x,h(i)}$), the estimated mean cumulative exposure for these workers was 38.1 (SD 78.5) mg·yr m^{-3} for respirable dust and 2.0 (SD 3.8) mg·yr m^{-3} for quartz. The estimated median cumulative exposure values were 7.0 mg·yr m^{-3} for respirable dust and 0.3 mg·year m^{-3} for quartz (Figure 2). The distribution of estimated cumulative exposure indicated that 10% of the workers had cumulative exposures higher than 109.0 mg·yr m^{-3} for respirable dust and 5.3 mg·yr m^{-3} for quartz (Figure 3).
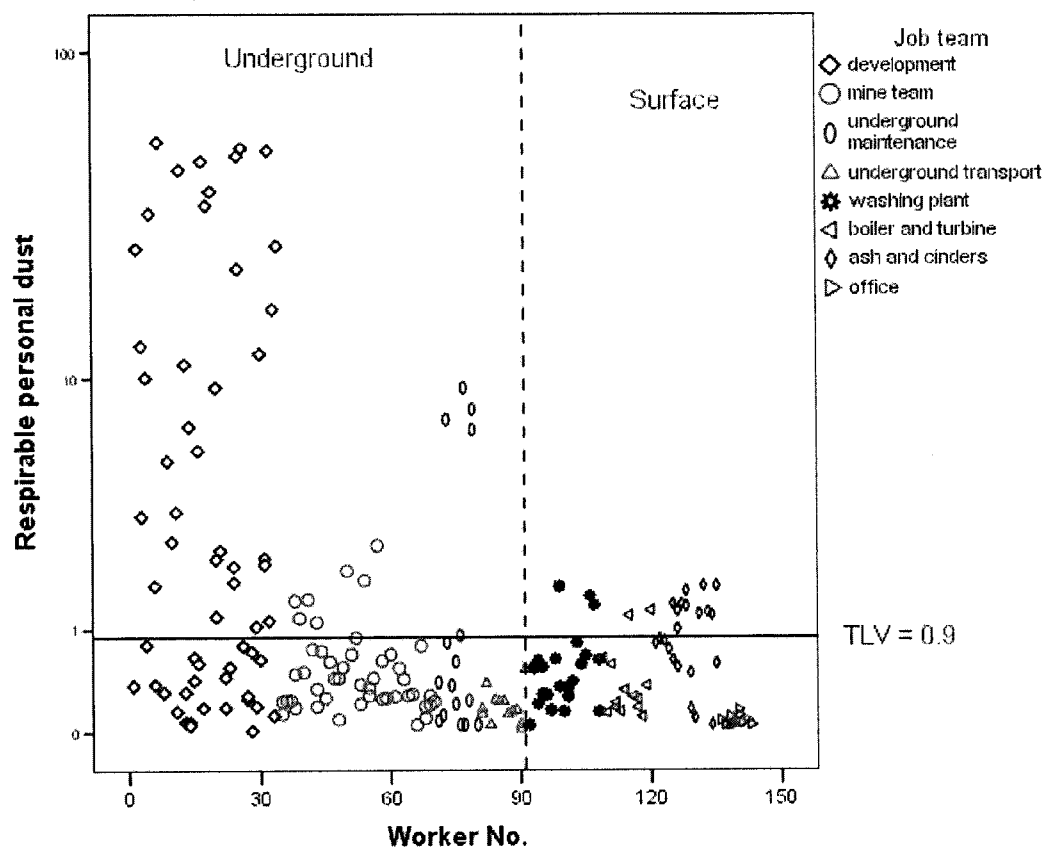
Fig. 1. Distribution of respirable personal dust exposure (mg m^{-3}) for 141 workers grouped by job team.

Table 1. Mean values, variance components and estimated long-term exposure levels among 141 coal mine workers in eight job teams.

Job teams	W^a	N^b	AM	GM(GSD)	$_{ww}S^2$	$_{bw}S^2$	$_{ww}R_{0.95}$	$_{bw}R_{0.95}$	$\mu_{x,h(i)}$
Respirable dust									
Development	34	58	10.30	1.96 (8.44)	4.45	0.10	3902.0	3.5	18.17
Mine team	36	47	0.66	0.47 (2.27)	0.66	0.03	24.2	2.0	0.56
Ug^c maintenance	10	16	2.35	0.58 (6.37)	3.30	0.29	1237.7	8.3	2.60
Ug transport	11	13	0.18	0.14 (2.13)	0.19	0.54	5.5	17.8	0.16
Washing plant	17	23	0.55	0.41 (2.29)	0.69	0	26.0	1	0.58
Boiler and turbine	12	14	0.42	0.31 (2.17)	0.04	0.63	2.2	22.5	0.32
Ash and cinders	15	22	0.95	0.73 (2.53)	0.86	0	37.9	1	1.13
Office	8	11	0.08	0.07 (1.53)	0.09	0.08	3.2	3.0	0.07
Respirable quartz									
Development	33	56	1.268	0.073 (11.10)	5.07	0.93	6812.6	43.8	0.889
Mine team	35	46	0.033	0.013 (2.78)	0.99	0.04	49.4	2.2	0.022
Ug maintenance	9	14	0.411	0.016 (11.05)	5.52	0	9995.7	1	0.222
Ug transport	7	8	0.007	0.006 (1.84)	0.21	0	6.0	1	0.009
Washing plant	11	16	0.017	0.011 (2.80)	1.06	0	56.6	1	0.019
Ash and cinders	12	19	0.038	0.020 (4.10)	1.99	0	252.1	1	0.054
Boiler and turbine	6	7	0.030	0.020 (2.58)	<0.001	<0.001	1	1	0.020
Office	6	7	0.007	0.006 (1.90)	0.41	0	12.3	1	0.007

$^a W$, number of workers; $^b N$, number of measurements; ^{c}Ug, underground; $_{ww}S^2$, within-worker variance component; $_{bw}S^2$, between-worker variance component; $_{ww}R_{0.95}$, ratio of 97.5th to 2.5th percentiles of the distribution of exposures within a worker; $_{bw}R_{0.95}$, ratio of 97.5th to 2.5th percentiles of between-worker distribution of exposures. $\mu_{x,h(i)}$, estimated worker-specific mean exposure in job team h.
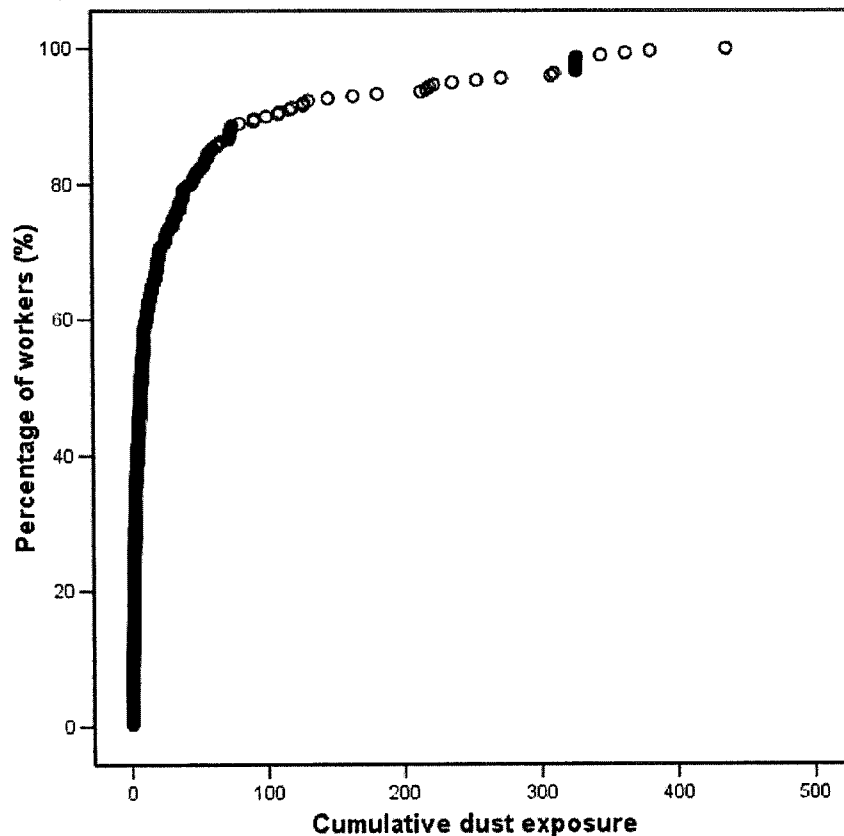
Fig. 2. Distribution of estimated cumulative respirable dust (mg·yr m^{-3}) among 299 coal mine workers.

DISCUSSION

The variability of the respirable dust exposure was higher among the underground workers than among workers at the surface. However, only workers in the development areas, who make tunnels mainly through hard rock, had markedly higher exposure than the surface teams. Mamuya *et al.* (2006) have described the exposure levels and the determinants of exposure for the underground workers in detail. For surface workers, the range of average exposure levels was similar to those reported at analogous plants in coal mines in the United States and Italy (Piacitelli *et al.*, 1990; Carta *et al.*, 1996).

Even though the day-to-day variability in exposure was very high, the eight job teams have relatively small ranges of between-worker exposure, indicating that the differences in mean exposure between workers within the job teams are quite low. Some of the between-worker variance components were estimated to be zero, which is not uncommon when using REML estimators (Rappaport *et al.*, 1999; Weaver *et al.*, 2001). Rappaport (1991) has suggested that a group is uniformly exposed when 95% of the individual mean exposures lies within a factor of 2.0 ($_{bw}R_{0.95} < 2$). A strict definition of uniformly exposed groups is not a prerequisite for identifying a

relationship between exposure and health outcome (Rappaport, 1991; Kromhout and Heederik, 1995). On the other hand, in our study, the establishment of uniformly exposed groups might have increased the validity of the estimated cumulative exposure.

In the hard rock work area, the $_{ww}R_{0.95}$ values indicate that the respirable dust and quartz exposure may vary from day to day by factors of 3902 and 9996, respectively. Different tasks such as drilling, blasting, lashing and roofing are associated with large differences in exposure (Mamuya *et al.*, 2006). The time spent on such intermittent working processes and the rotation between these tasks is presumably the main explanations for the high day-to-day variability. This spatial variability might also partly be caused by an unpredicted geological environment in which the rock structures can differ from site to site. The high within-worker variance component in the underground maintenance team is presumably caused by their alternating work in highly exposed hard rock areas and in less-exposed underground areas. Although less pronounced, the within-worker variability is considerable in the raw coal and the processed coal areas, presumably related to day-to-day rotation between tasks. An alternative grouping by job task was not considered in this study. Construction of subgroups based on job task would have led
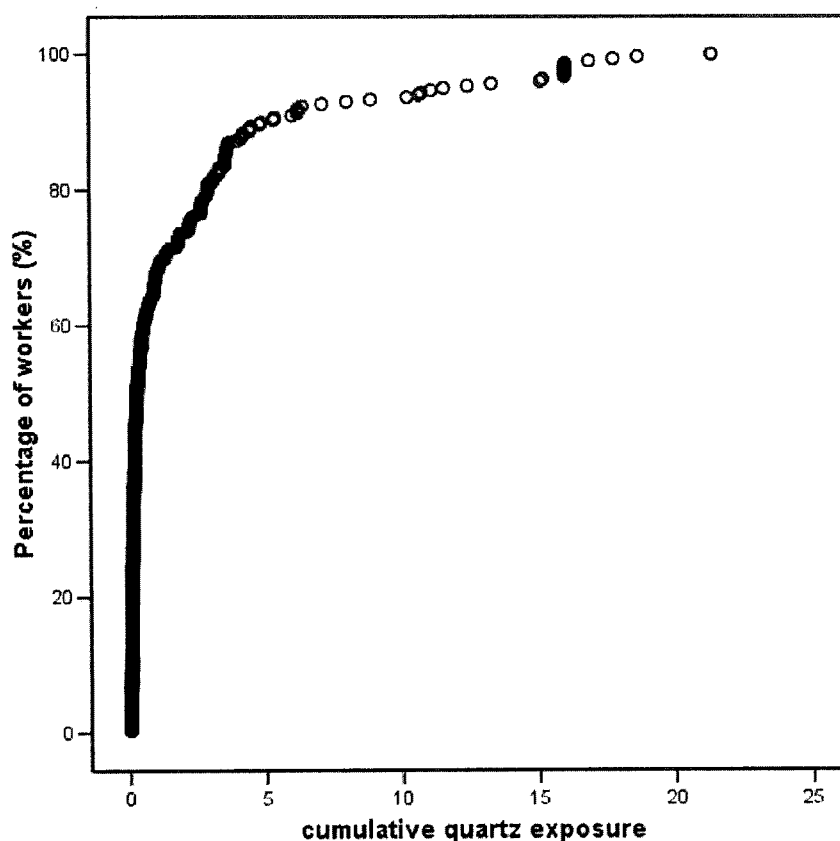
Fig. 3. Distribution of cumulative respirable quartz (mg yr m^{-3}) among 299 coal mine workers.

to many subgroups with few measurements. Further, the extensive job rotation within the job teams makes estimating cumulative exposure based on task grouping difficult.

The contrast in exposure between the job team subgroups was apparently high due to the large variance component between the groups versus within the groups. A high contrast in exposure is also expected based on the differences in the mean exposure values in the job teams. However, common within-worker variance across the subgroups is assumed when using variance components to quantitatively assess contrast as well as attenuation of exposure–response curves (van Tongeren et al., 1997; Tielemans et al., 1998; Mwaiselage et al., 2005). In the present study this assumption was obviously not met. Similar to other studies (van Tongeren et al., 1997; Symanski et al., 2000) also other assumptions such as equal number of workers in each group, equal number of repeated samples per worker and absence of confounding variables were violated in the present estimation of attenuation. When violating such assumptions the estimated attenuation should not be used for adjusting exposure–response associations (Kromhout et al., 2005). From an exposure–response study of lung function in the carbon black industry, van Tongeren et al. (1999) concluded that despite the

violation of most assumptions, including equal variance components across groups, the similarities in predicted and observed exposure–response relations and standard errors are indicative of the robustness of equation for attenuation. Burstyn et al. (2005) also suggested that bias caused by ignoring the heteroscedastic measurement error is unlikely to be large enough to alter the conclusion about the direction of exposure–disease association. However, it is still unclear whether these conclusions could be generalized. Hence, the apparently high contrast and the low attenuation for the job team grouping might only be taken as rough indications of sufficient grouping efficiency in a subsequent study on the association between current dust exposure and respiratory effects.

Our tertiles for cumulative respirable dust exposure of 2.8 and 18.4 mg·year m^{-3} with a mean exposure time of 10.2 years were lower than those recently reported for 857 South African coal miners (20.1 and 72.8 mg year m^{-3}), with the average years of exposure ranging from 3.3 to 10 for the worker groups included (Naidoo et al., 2004). In the South African study, the overall prevalence of pneumoconiosis was 2–4%, and cumulative dust exposure was associated with a decline in respiratory function. The mean cumulative respirable dust exposure (38.1 mg year m^{-3}) in our study was higher than estimated in a national

study of pneumoconiosis among 1270 coal miners in the United States (15.5 mg·yr m^{-3}) (Seixas *et al.*, 1991), with a mean exposure time of 12.8 years. However, comparing cumulative exposure levels between studies in coal mining is not straightforward because the methods used for estimating and assigning exposure levels to individual workers differ.

Based on data from the British Pneumoconiosis Field Research, Soutar *et al.* (2004) estimated that, at a respirable quartz exposure of 0.3 mg m^{-3} for 15 working years, corresponding to a cumulative concentration of 4.5 mg·year m^{-3}, the risk of category II silicosis for coal miners was 20%. In our study, ~11.0% of the study population had an estimated cumulative respirable quartz concentration exceeding this level. The South African study by Naidoo *et al.* (2004) did not report quartz exposure.

In our study, the reported time worked in the coal mine, which was used for calculating cumulative exposure, was based on interviewing the workers. Thus, some recall bias is probably present since the occupational history spans up to two decades. Moreover, we did not collect any information on whether the workers had left the mine temporarily for any reason such as lack of explosives, market problems or problems with the washing plant, all of which may have contributed to overestimating cumulative exposure. Nevertheless, according to the management the annual production rate had been fairly constant during the years from 1988, and no major changes had taken place in the production processes. The exposure was measured in two time periods in recent years, covering work in areas with different quartz content and the major work processes for underground workers (Mamuya *et al.*, 2006) and for surface workers. However, the overall representativity of the measurements, with relatively few repeated samples in some job teams, cannot be ascertained. Another problem is the risk of misclassifying workers into exposure groups based on job team. In the job history interview, the number of years in the mine focused on employment in the respective job teams. Although the job teams practice extensive job rotation, some workers in the development and hard rock area might not have been drilling, thus resulting in an overestimation of cumulative dust and quartz for these workers. In addition the exposure metrics in this analysis did not distinguish exposure intensity and duration, which is a major draw back for the cumulative exposure index (Smith, 1992; Seixas *et al.*, 1993). Also the cumulative exposure estimated might not do well for quartz-related risk where the residence time is important (Jahr, 1974; Vacek, 1997).

To our knowledge, this is the first attempt to group workers based on exposure variability for estimating cumulative dust and quartz in labour-intensive coal mines in developing countries. The exposure estimates will be used in analysing the exposure–response relationships for respiratory health effects.

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