

# **Dust exposure and respiratory health problems in a labour-intensive coal mine in Tanzania**

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**Dust exposure and respiratory health problems in a labour-  
intensive coal mine in Tanzania**

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**Centre for International Health**

**Section for Occupational Medicine**

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Dedicated to my adorable wife Candida and  
my children Amadeus, Irene, Ana, Adeline and Erick



**Contents**

***ACKNOWLEDGEMENTS***

***LIST OF ARTICLES***

***LIST OF ABBREVIATIONS***

***SUMMARY***

***INTRODUCTION* ..... 1**

**Coal mining..... 1**

**Mixed coal mine dust ..... 1**

**Occupational dust exposure in coal mines ..... 2**

**Respiratory health problems among coal miners ..... 3**

**Need for a new study..... 6**

***AIM OF THE STUDY* ..... 7**

**Broad objective ..... 7**

**Specific objectives..... 7**

***COAL MINING IN TANZANIA* ..... 9**

**Geological description of Tanzanian coal..... 9**

**Kiwira Coal Mine ..... 10**

<b><i>WORK ENVIRONMENT AND JOB CATEGORIES</i></b> .....	<b>11</b>
<b>Development job team</b> .....	<b>11</b>
<b>Mine team</b> .....	<b>12</b>
<b>Underground maintenance</b> .....	<b>13</b>
<b>Underground transport team</b> .....	<b>13</b>
<b>Washing plant</b> .....	<b>14</b>
<b>Boiler and turbine</b> .....	<b>15</b>
<b>Ash and cinders</b> .....	<b>15</b>
<b>Office workers</b> .....	<b>16</b>
<b><i>MATERIAL AND METHODS</i></b> .....	<b>17</b>
<b>Study area</b> .....	<b>17</b>
<b>Study design</b> .....	<b>17</b>
<b>Study subjects</b> .....	<b>17</b>
Workers for the epidemiological study.....	17
Workers for dust sampling.....	18
<b>Ethical clearance</b> .....	<b>19</b>



<b>Data collection and outcome variables.....</b>	<b>20</b>
Questionnaire .....	20
Pulmonary functioning.....	21
Exposure assessment.....	22
<b><i>PROCESSING OF EXPOSURE DATA .....</i></b>	<b>23</b>
<b><i>STATISTICAL ANALYSIS .....</i></b>	<b>25</b>
<b><i>SYNOPSIS OF PAPERS.....</i></b>	<b>28</b>
<b>Paper I .....</b>	<b>28</b>
<b>Paper II.....</b>	<b>29</b>
<b>Paper III .....</b>	<b>30</b>
<b>Paper IV .....</b>	<b>32</b>
<b><i>DISCUSSION.....</i></b>	<b>33</b>
<b>Methodological considerations .....</b>	<b>33</b>
Study design.....	33
Validity .....	33
Internal validity.....	33
External validity.....	35
Confounding .....	36
Statistical analysis.....	37

Questionnaires.....	37
Pulmonary function testing.....	38
Exposure assessment.....	38
<b>Main discussion .....</b>	<b>39</b>
Occupational coal dust exposure .....	39
Exposure variability .....	40
Dust exposure and lung functioning .....	41
Dust exposure and respiratory symptoms .....	43
<b><i>STUDY CONCLUSIONS .....</i></b>	<b><i>44</i></b>
<b><i>RECOMMENDATIONS FOR FUTURE RESEARCH .....</i></b>	<b><i>45</i></b>
<b><i>RECOMMENDATIONS FOR PREVENTIVE MEASURES.....</i></b>	<b><i>46</i></b>
<b>General recommendations .....</b>	<b>46</b>
<b>Specific work area–related recommendations.....</b>	<b>46</b>
<b><i>RECOMMENDATIONS FOR POLICY MEASURES .....</i></b>	<b><i>48</i></b>
<b><i>REFERENCES .....</i></b>	<b><i>49</i></b>
<b><i>PAPER I-IV</i></b>	
<b><i>APPENDIX 1-6</i></b>	

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## List of articles

The thesis is based on the following articles referred to in the text by roman numerals.

### Paper I

Simon H.D. Mamuya, Magne Bråtveit, Julius Mwaiselage, Yohana J.S. Mashalla and Bente E. Moen (2006). **High exposure to respirable dust and quartz in a labour-intensive coal mine in Tanzania.** Ann Occup Hyg 50(2):197–204.

### Paper II

Simon H.D. Mamuya, Magne Bråtveit, Julius Mwaiselage and Bente E. Moen (2006). **Variability of exposure and estimation of cumulative exposure in a manually operated coal mine.** Ann Occup Hyg Doi:10.1093/annhyg/me1031.

### Paper III

Simon H.D. Mamuya, Magne Bråtveit, Yohana J.S. Mashalla and Bente E. Moen. **Airflow limitation among workers in a labour-intensive coal mine in Tanzania.** Submitted.

### Paper IV

Simon H.D. Mamuya, Magne Bråtveit, Yohana J.S. Mashalla and Bente E. Moen. **High prevalence of respiratory symptoms among development workers in a manually operated coal mine in a developing country.** Submitted.

## **List of abbreviations**

AM	arithmetic mean
ANOVA	analysis of variance
FEV <sub>1</sub>	forced expiratory volume in 1 second
FVC	forced vital capacity
GM	geometric mean
SD	standard deviation
TLV	threshold limit value

## ***Summary***

Dust exposure and respiratory health problems were studied among randomly selected workers in a coal mine in Tanzania. The aim of the study was to assess the personal respirable dust and quartz exposure and the prevalence of respiratory problems and to present recommendations on how to improve the situation.

An epidemiological cross-sectional study was carried out at the Kiwira Coal Mine in Tanzania. Dust exposure was measured during two periods in 2003 and 2004. In total, 204 dust samples were taken from 141 workers. The surveys involved 299 workers randomly selected from 8 job teams including development, mine, underground maintenance, underground transport, washing plant, boiler and turbine, ash and cinders and office workers. The study conducted a face-to-face standardized interview to collect information on demographic characteristics, work history, previous diseases, acute respiratory symptoms, chronic respiratory symptoms and smoking habits. Lung functioning was assessed using a Vitalograph Alpha III portable spirometer according to American Thoracic Society (1995) recommendations.

Personal respirable dust was sampled using a SKC Sidekick pump with a flow rate of  $2.2 \text{ l} \cdot \text{min}^{-1}$ . Respirable dust samples were analysed for quartz by X-ray diffraction on a silver membrane filter using the US National Institute for Occupational Health and Safety method 7500. The individual cumulative exposure to respirable dust or quartz ( $\text{mg} \cdot \text{year} \cdot \text{m}^{-3}$ ) for each worker was estimated. Nitrogen dioxide ( $\text{NO}_2$ ), ammonia ( $\text{NH}_3$ ), carbon monoxide (CO) and sulphur dioxide ( $\text{SO}_2$ ) gas concentrations were



assessed using electrochemical sensors (Dräger PAC III) and using Dräger detector tubes.

The statistical methods used in analysing the data included Student's *t*-test, analysis of variance, the chi-square test, multiple linear regression models, logistic regression modelling and one- and two-way random effects models.

The workers in the development team had the highest exposure to respirable dust and quartz (geometric means  $1.80 \text{ mg} \cdot \text{m}^{-3}$  and  $0.073 \text{ mg} \cdot \text{m}^{-3}$ , respectively). The percentages of samples exceeding the threshold limit values of  $0.9 \text{ mg} \cdot \text{m}^{-3}$  for respirable (bituminous) coal dust and  $0.05 \text{ mg} \cdot \text{m}^{-3}$  for respirable quartz, respectively, were higher in the development team (55% and 47%) than in the mining team (20% and 9%). Drilling in the development team was the work task associated with the highest exposure to respirable dust and quartz ( $17.37 \text{ mg} \cdot \text{m}^{-3}$  and  $0.611 \text{ mg} \cdot \text{m}^{-3}$ , respectively). The exposure models for the development section showed that blasting and pneumatic drilling time were the major determinants of respirable dust and quartz, explaining 45.2% and 40.7% of the variance, respectively. In the mining team, only blasting significantly determined respirable dust.

For most *a priori* job teams, the within-worker variance component was considerably higher than the between-worker variance component. The high contrast in exposure between the teams together with the estimated low attenuation of the theoretical curve led to the conclusion that grouping by job team would be appropriate for studying the association between current dust exposure and respiratory effects. Based on the estimated worker-specific mean exposure in the job teams and the job history, the arithmetic mean cumulative exposure for workers who participated in the

epidemiological part of the study was  $38.1 \text{ mg} \cdot \text{year} \cdot \text{m}^{-3}$  for respirable dust and  $2.0 \text{ mg} \cdot \text{year} \cdot \text{m}^{-3}$  for quartz.

The prevalence of the ratio of forced expiratory volume in 1 second ( $\text{FEV}_1$ ) to forced vital capacity (FVC) being less than 0.7 among the workers was 17.3%. Workers in the development team (20.5%) had the highest prevalence of  $\text{FEV}_1\% < 80\%$ . The estimates of the effects of cumulative exposure on  $\text{FEV}_1/\text{FVC}$  were 0.015% per  $(\text{mg} \cdot \text{year} \cdot \text{m}^{-3})$  for respirable dust and  $-0.3\%$  per  $(\text{mg} \cdot \text{year} \cdot \text{m}^{-3})$  for respirable quartz. In logistic regression models, the odds ratios for airway limitation ( $\text{FEV}_1/\text{FVC} < 0.7$ ) for the workers in the highest decile of cumulative dust and quartz exposure versus the referents were 4.36 (95% confidence interval (CI): 1.06, 17.96) for dust and 3.49 (95% CI 0.92, 13.21) for quartz. The upper 10% of workers grouped by cumulative dust and quartz exposure also had higher odds ratios (OR) for predicted  $\text{FEV}_1\% < 80\%$  than the reference group OR: 10.38 (95% CI 1.38, 78.13) for dust and 14.18 (95% CI 1.72, 116.59) for quartz.

The workers from the development team had a higher self-reported prevalence of acute symptoms of breathlessness (OR = 2.96, 95% CI 1.44–6.11) and blocked nose (OR = 2.47, 95% CI 1.10–5.56) than the other production workers. In addition, development workers had more chronic symptoms of breathlessness (17.0%) than the other production workers (3.9%) ( $P = 0.001$ ). The highest decile of exposure to respirable dust was associated with cough (OR = 2.91, 95% CI 1.06–7.97), as was the highest decile of exposure to respirable quartz (OR = 2.87 (95% CI 1.05, 7.88), compared with the reference.

This study showed that workers in a coal mine are exposed to high levels of respirable dust and quartz, especially drillers and blasters. This study also showed that the development workers had more acute and chronic respiratory symptoms than other production workers. It also revealed an exposure–response relationship between respirable coal mine dust and quartz and airway limitation measured by spirometry. Immediate actions that could improve the situation include implementing effective dust control together with improved training and education programmes for the workers. Priority should be given to workers performing drilling and blasting in the development sections of the mine. Further needs include policies on exposure and health surveillance and appropriate enforcement mechanisms in Tanzania.



## ***Introduction***

### **Coal mining**

Coal mining is the extraction of coal from the earth for use as fuel. Coal may be found either as surface outcrops or in underground seams. Coal is ranked according to the carbon content; thus, anthracite is ranked highest and is followed in descending order by bituminous coal, sub bituminous coal and lignite. Dust emitted during the mining processes is a specific risk factor for respiratory health among miners (1-4).

### **Mixed coal mine dust**

Coal mine dust is not uniform and comprises more than 50 different elements and their oxides, including trace metals, inorganic minerals and crystalline silica (5, 6). Trace metals include boron, cadmium, copper, nickel, iron, antimony, lead and zinc. Some of the trace elements can be cytotoxic and carcinogenic in experimental models (7).

Generally, the most common clay minerals found in coal are kaolin, mica, pyrite, titanium, calcite, sulphur, sodium, magnesium and silica. Organic compounds in coal include methane, benzene, phenols, naphthalene and some polycyclic aromatic hydrocarbons. Airborne respirable dust in underground coal mines has been estimated to consist of 40–95% coal, and the rest is mixed dust originating from fractured rock on the mine roof or from the coal seam (8). Quartz levels tend to vary inversely with coal rank, being highest in low-ranking coal seams (9, 10). The economically most important types of coal vary from subbituminous to anthracite coal, with carbon content varying from 79% to 94% (6).

## **Occupational dust exposure in coal mines**

Increasing demand for coal during the Industrial Revolution provided an incentive for accessing deep coal reserves, and by the middle of the twentieth century most global coal was produced from underground operations. Dust levels during underground mining differ significantly according to the location in the mine (9, 11-13) and occupation (6, 12, 14, 15). Workers at the coal face have higher dust exposure than workers further away from the face (12, 16, 17). A study in the Netherlands also noted different levels of exposure between different seams (18). Previous coal mine studies (19-24) recognized and practised the importance of an effective grouping scheme based on dust exposure for epidemiological studies.

Many studies of coal mines have been performed. A study in 20 mines in the United Kingdom before 1969 showed respirable dust levels analogous to those in United States at about the same time, ranging from 1.2 to 8.2 mg · m<sup>-3</sup> (9, 25). Studies from South Africa and Germany between 1955 and 1970 showed respirable dust exposure of 3.9–12.5 mg · m<sup>-3</sup> and 6–23 mg · m<sup>-3</sup>, respectively (16, 26). More recent studies in the United Kingdom, the United States and Australia showed respirable dust exposure below 2 mg · m<sup>-3</sup> (10, 14) (Table 1). After the 1980s, dust levels were generally reduced in industrialized countries through regulatory action and technical measures (27-30).

Today the main problems of respiratory health among miners are probably in developing countries, where coal mining is relatively new, there are few regulations and

the enforcement of these regulations is uncertain. Very few studies have been performed in mines in developing countries.

### **Respiratory health problems among coal miners**

Coal dust is a serious hazard in mining, causing coal workers' pneumoconiosis and progressive massive fibrosis (2, 22). The extent and nature of respiratory diseases among miners was extensively studied before 1950, but those studies lacked any link to the quantity of dust exposure (3, 4, 31). A significant association between exposure to coal dust and the development of chronic respiratory symptoms has been documented among workers employed in coal mining (27, 32-42). In general, more dusty environments are associated with a higher prevalence of the symptoms of chronic diseases (43).

Cross-sectional spirometry studies from various countries have documented a reduced FEV<sub>1</sub> among miners related to cumulative dust exposure (36, 44-49). Most of these studies also noted that smoking contributed equally to dust exposure in reducing lung functioning (50-53). Some cohort studies have shown that longitudinal decline in lung functioning is linked to dust exposure (32, 54-58). Age contributes significantly to the decrease in lung functioning. Further, young miners have steeper declines in lung functioning than experienced workers. The ratio of FEV<sub>1</sub> to FVC decreased as the dust exposure increased (48, 57, 59).

Different authors use different units for cumulative exposure, and conversion factors must be used in some cases to facilitate the comparison of findings in various studies.

Cumulative exposure units can be converted from  $\text{mg} \cdot \text{year} \cdot \text{m}^{-3}$  to  $\text{g} \cdot \text{hour} \cdot \text{m}^{-3}$  using the factors of 1740 hours per year and 1000 mg per gram based on the assumption that each miner works about 1740 hours per year (45); thus,  $1 \text{ mg} \cdot \text{year} \cdot \text{m}^{-3} = 1.74 \text{ g} \cdot \text{hour} \cdot \text{m}^{-3}$ .



Study	Reference no.	Study design	n	Estimated decline in FEV <sub>1</sub> : ml per (g · h · m <sup>-3</sup> )	Average dust levels (mg · m <sup>-3</sup> )	Decline in FEV <sub>1</sub> /FVC: % per (g · h · m <sup>-3</sup> )	Symptoms
<b>National Study on Coal Workers' Pneumoconiosis – United States</b>							
Attfield 1985	(53)	Longitudinal		2.4			
Parobeck & Tomb (1979)	(15)	Cross-sectional			0.4–1.5		
Attfield & Hodous (1992)	(44)	Cross-sectional	7140	0.69		0.008	
Seixas et al. (1992)	(27)	Cross-sectional	1185	3.2*		0.05*	CB 21%, SB 22%, P 32%, W 27%
Seixas et al. (1993)	(58)	Longitudinal	977	3.4*		0.04*	
Hennerberger & Attfield (1996)	(56)	Cross-sectional	1915	0.28*			
Hennerberger & Attfield (1997)	(59)	Cross-sectional	1915	0.28*		0.010*	CB 35%, SB 43%, W 42%
<b>Pneumoconiosis Field Research – United Kingdom</b>							
Jacobsen et al. (1970)	(9)	Longitudinal			1.2–8.2		
Rogan et al. (1973)	(36)	Cross-sectional	3581	0.6			
Love & Miller (1982)	(54)	Longitudinal	1677	0.36			
Soutar & Hurley (1986)	(43)	Cross-sectional	4059	0.76		0.005	
<b>Other studies</b>							
Naidoo et al. (2006, South Africa)	(17, 42)	Cross-sectional	684		0.4–2.9		CC 5%, CB 9%, SB 3%, W 6%
Naidoo et al. (2005, South Africa)	(61)	Cross-sectional	684	0.03*	0.4–2.9		
Carta et al. (1996, Sardinia, Italy)	(32)	Longitudinal		5.7*	1.7–3.0		
Kizil & Donoghue (2002, Australia)	(14)	Cross-sectional			0.3–0.9		
Wang et al. (2000, China)	(60)	Cross-sectional					CC 47%, CB 36%, SB 77%
Mamuya et al. (2006, Tanzania)	(13, 64)	Cross-sectional	141		0.1–10.3		
Current study, Tanzania		Cross-sectional	250			0.009*	CC 6%, CB 13%, SB 6%, W 8%

CB: chronic bronchitis. SB: shortness of breath. P: phlegm. W: wheezing. CC: chronic cough. \*Converted from: per (mg · year · m<sup>-3</sup>).

Table 1 Reviews of studies on coal dust and respiratory health problems among miners

## **Need for a new study**

Although many studies have been published on respiratory effects in coal mining, the current study was done since no study from a manually operated coal mine had described the relationship between coal dust exposure and the respiratory health problems among different groups of coal workers. One aim was to produce baseline data on which interventions and other epidemiological studies could be based in the mine selected for this study. The recommendations given would contribute to minimizing the dust exposure of vulnerable and poor working people. In addition, this study was intended to raise awareness of the hazards and the risks of coal mine work in general. Stakeholders could then use the current results to produce a sustainable programme for controlling dust problems in the mines both in Tanzania and in other developing countries. Policy-makers could use the information to formulate guidelines on environmental exposure in the mines in Tanzania and other similar countries. Fig. 1 links the exposure and outcome variables.

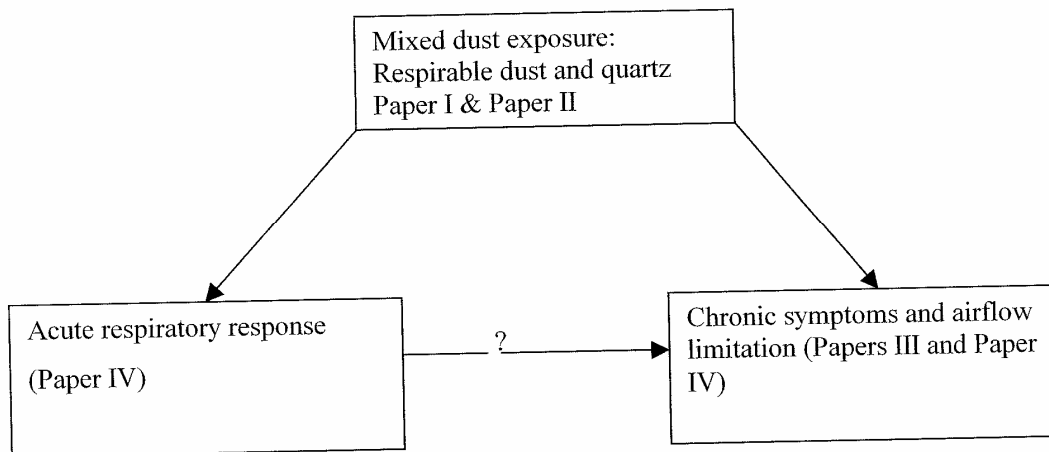


Fig. 1. Schematic diagram showing the relationship between mixed dust exposure and respiratory health problems

## ***Aim of the study***

### **Broad objective**

The general objective of this study was to describe and characterize the mixed coal dust exposure and to assess respiratory health problems related to the dust exposure among workers in a coal mine in Kiwira, Tanzania in order to obtain relevant information that can be used for planning and implementing preventive strategies.

### **Specific objectives**

1. To assess the personal exposure to respirable dust and quartz among workers in the mine (Paper I and Paper II).
2. To identify potential determinants of personal exposure to respirable dust and quartz among underground coal mine workers (Paper I).

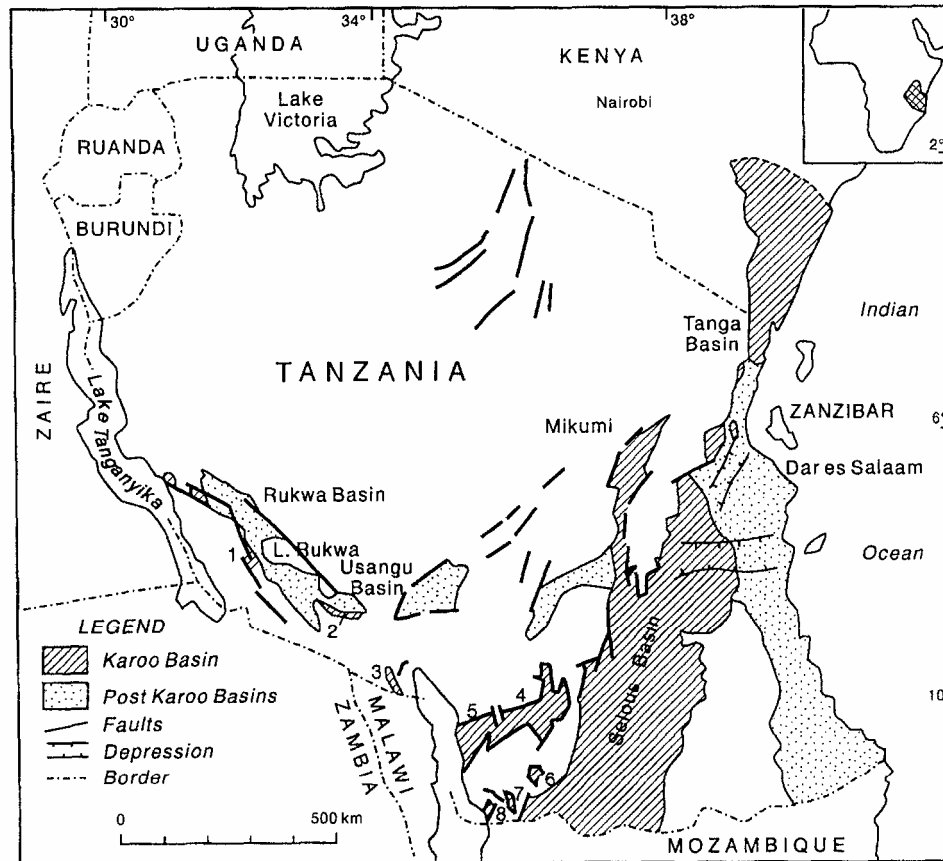
3. To describe the relationship between cumulative respirable dust and quartz exposure and ventilatory function among workers in the coal mine and to examine the dose–response relationship (Paper III).

4. To determine the prevalence of respiratory health symptoms among workers in the mine (Paper IV).

## **Coal mining in Tanzania**

### **Geological description of Tanzanian coal**

The coal found in Tanzania's coal fields was deposited during a period of 35 million years (61). The coal is found in thick shallow coal seams, with most reserves in the southern highland area. The coal seams were formed during two periods in the early Permian Epoch and late Permian Epoch. The coal is associated with non-marine terrestrial clastic sedimentary sequences, most commonly mud rock and sandstone, assigned to the Karoo supergroup. The coal seams, which have a cumulative thickness of 6.80 m, occur in the shale-sandstone facies of Mchuchuma Formation of Artinskian to Kungurian. Kiwira has bituminous coal ranging from high volatile C bituminous to high volatile A bituminous coal (61, 62). Fig. 2 shows the Kiwira Coal Mine location and other coal resources in Tanzania.



- |                                     |                                 |
|-------------------------------------|---------------------------------|
| 1. Namwele-Mkomolo, Muze coalfields | 5. Ketewaka-Mchuchuma coalfield |
| 2. Galula coalfield                 | 6. Njuga coalfield              |
| 3. Songwe-Kiwira Basin              | 7. Mhukuru coalfield            |
| 4. Ruhuhu Basin                     | 8. Mbamba Bay coalfield         |

Figure 2: Distribution of Karoo basins and coalfields in Tanzania

### Kiwira Coal Mine

Knowledge of the existence of coal reserves in Tanzania can be traced back to 1896 following a geological investigation made by Wilhelm Bornhardt, a geologist from Germany. He surveyed the Songwe Kiwira area and described the general succession of the Karoo strata as well as several outcropping coal fields. Successive surveys of coal in Tanzania took place between 1900 and 1950 (63). The first recorded coal exploitation in

the country was in 1953 following a mine lease granted to A. von Voitenberg on part of Ilima Hill. The ownership of the Ilima mine was transferred to the State Mining Corporation in 1976.

The coal seam in Kiwira is accessed through the adit level, where networks of underground roads are constructed for extracting and transporting coal to the surface for processing. Wooden props (timber) with caps (crossbars) are set to support the exposed roof and are allowed to remain in place as the face is advanced. Props with caps are also used to protect the conveyor, the working faces and the intake and return airways. A main exhaust fan placed outside at a higher elevation ventilates the mine.

### ***Work environment and job categories***

The study population studied in Kiwira Coal Mine included workers from the production department, which comprised eight different job teams; development, mine, underground maintenance, underground transport, washing plant, ash and cinders, boiler and turbine and office.

#### **Development job team**

Workers in the development team create mining paths for the miners to harvest and extract coal. They are mainly located at the development site, where they create a new mine face and a conveyor roadway with a return roadway connected by a crosscut. They use a pneumatic jack for drilling holes through hard rock and use detonators for blasting.



Fig. 3. Pneumatic drilling in development (photograph by Simon H.D. Mamuya)

### **Mine team**

Workers in the mine team are responsible for reducing the size of blasted coal and shovelling it to the conveyor panel. They mainly work at the mine face, and their tasks involve drilling the coal face, blasting the coal seam and lashing coal. They normally use an electric drill for drilling through the face.



Fig. 4. Lashing coal in the mine team (photograph by Simon H.D. Mamuya)



## **Underground maintenance**

The underground maintenance team is involved in maintaining utilities and major equipment at the development sites and at the mine face. They are responsible for plumbing and electricity work and work closely with ventilation workers to ensure that the work in the development and the mine runs smoothly.



Fig. 5. A worker in underground maintenance repairing a winch (photograph by Simon H.D. Mamuya)

## **Underground transport team**

The underground transport team is responsible for operating the locomotive transporting workers and supplies to the mine and for maintaining the rail lines and for ensuring that the line is clear of any coal that might have fallen out of the wagon onto the rail. They mostly work in the main tunnel.



Fig. 6. Underground transport worker fixing rail lines (photograph by Simon H.D. Mamuya)

### **Washing plant**

Washing plant workers are involved in operating the plant for grinding and screening coal to the required market size and for cleaning the coal under pressurized water to remove the sulphur content. They also separate the unwanted particles from the washed coal.



Fig. 7. Coal conveyed to the washing section (photograph by Magne Bråtveit)

### **Boiler and turbine**

The boiler operators are responsible for controlling coal and water by a control panel. The operators in the turbines are responsible for regulating the steam and pressure in the turbines for producing electricity that is used in the mine or is sold to the national grid.



Fig. 8. Boiler and turbine section (photograph by Magne Bråtveit)

### **Ash and cinders**

Workers in ash and cinders are responsible for feeding coal to the boiler conveyor belt and for removing ash and cinder remnants from the boiler to the disposal area. They push trolleys with fine ash to the damping area.



Figure 9. Workers pushing trolley with ash and cinders (Photograph by Mamuya SHD)

### Office workers

The study also comprised office workers from the administration and power plant. Their socioeconomic status was similar to that of the production workers.



Fig. 10. Office workers from the administration block (photograph by Simon H.D. Mamuya)

## ***Material and methods***

### **Study area**

The Kiwira Coal Mine is located in the Mbeya Region of Tanzania about 1000 km from Dar es Salaam and 100 km from Mbeya Town. It is located at the boundary of the Tukuyu and Kyela districts. It has about 600 workers, of whom 240 are involved in underground tasks. It has operated at a capacity of 150,000 tonnes of bituminous coal per year since 1988.

### **Study design**

This dissertation is based on a cross-sectional study design. Exposure data were sampled in two periods, and the workers' job history was used to calculate the individual cumulative exposure to respirable dust and quartz. Lung functioning was measured once and respiratory symptoms were elicited once among the workers selected.

### **Study subjects**

#### *Workers for the epidemiological study*

Kiwira Coal Mine management provided the total list of about 556 workers. The 220 workers excluded from the study included managers, assistant managers and heads of section due to their high socioeconomic status; surface workers in carpentry, masonry, garage, foundry, welding, machine workshop and surveying due to other types of exposure that might reduce the validity of our study; and temporary workers (64). In total, 336 workers were invited to participate. Of these, the final study population included 318 workers (303 men and 15 women) since 18 declined to participate, giving a

response rate of 94.6%. The women were excluded before statistical analysis due to their low number. A further two workers with bronchial asthma and two with tuberculosis were excluded from the analysis. Of the 299 workers remaining in the study, 47 were in development, 78 in the mine team, 30 in underground transport, 34 in underground maintenance, 23 in the washing plant, 17 in boiler and turbine, 21 in ash and cinders and 49 in office work.

#### *Workers for dust sampling*

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. Dust was sampled 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 the US National Institute for Occupational Health and Safety (65) 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, workers from the first sampling period could be reselected, and the number of measurements allocated to each member of the job team was based on the exposure concentrations obtained from the first period, which were aggregated into low, medium and high exposure (66). Due to higher expected variability for the most highly exposed workers, the available 100 samples were planned to be distributed to the low-, medium- and high-exposure groups in the proportions of 1:3:5 as indicated by Loomis et al. (67). 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. Five workers declined to participate, and due to the time limit for conducting the study, 5 other 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. In the two measuring periods, 204 respirable dust samples were taken from 141 workers. The number of samples per worker ranged from 1 to 3.

### **Ethical clearance**

Ethical clearance was obtained from the Western Norway Regional Committee on Medical Research Ethics and the National Institute for Medical Research, Tanzania. The research permit was obtained from the Tanzania Commission for Science and Technology. There was institutional consent, since the administration of the mine was informed of the project and allowed to assist the study. Each worker was informed orally about the aim of the study and agreed to participate voluntarily.

## **Data collection and outcome variables**

### *Questionnaire*

The coal mine workers were interviewed using a standardized set of questions. The questionnaire consisted of three parts, including personal and work characteristics, smoking habits and respiratory health symptoms, including previous diseases. The questionnaire was prepared in English and was translated into Swahili, the national language of Tanzania, before it was used (68, 69). The questionnaire was pretested among 30 selected coal mine workers and discussed for the clarity of the questions before the study started. The questions on personal and work characteristics included sex, age, education level, employment history, years worked in Kiwira Coal Mine and years in dusty work elsewhere.

Questions on acute symptoms were elicited using a modified optimal symptom score questionnaire (70) and scored on a 5-point Likert scale as never (1), mild (2), moderate (3), severe (4) or very severe (5). Workers were asked whether they had the following symptoms: dry cough, shortness of breath, wheezing, stuffy nose, running nose and sneezing during or after the previous shift. Before statistical analysis, the response was dichotomized to no (never) and yes (mild, moderate, severe and very severe).

A modified version of the British Medical Research Council questionnaire on respiratory symptoms (71) included a set of questions on chronic symptoms of cough, breathlessness and wheezing. The subjects were also asked whether they had bronchial asthma and/or other chronic illnesses such as tuberculosis and bronchitis. Further, the



workers were asked whether they had injuries or operations affecting the chest, and whether they had heart problems, pneumonia, pleurisy, pulmonary tuberculosis, bronchial asthma or any other chest problems in the past 3 years. Workers with any of these pulmonary problems were excluded from the analysis.

Current smokers were defined as those who were smoking at the time of the study or those who had smoked more than one cigarette a day and stopped less than 1 year before the study. Ex-smokers were those who had smoked previously and stopped more than a year previously. The year they stopped smoking and the numbers of cigarettes smoked per day were also recorded. Never-smokers were defined as individuals who had never smoked.

#### *Pulmonary functioning*

Pulmonary functioning was assessed using a Vitalograph Alpha III portable spirometer (model 6000, Vitalograph Ltd., UK). Expired air was measured with the Vitalograph-Alpha using a Fleisch-type pneumotach while the attached microprocessor displayed the data on the screen. The spirometer was calibrated daily with a 1-litre precision syringe (catalogue no. 20.408, Vitalograph) and operated within a temperature range of 20–25°C. Of the 303 workers assessed, 282 had acceptable spiograms. The forced expiratory manoeuvres were explained to the workers. The tests were conducted according to American Thoracic Society (ATS) recommendations (72). Usually the subjects required two or three training measurements before three technically successful measurements were obtained. The subjects were examined in a standing position and were not using a nose clip. The maximum forced expiratory volume in one

second (FEV<sub>1</sub>) and maximum forced vital capacity (FVC) were recorded. The predicted spirometric values (FEV<sub>1</sub> and FVC) were derived from the regression equation for healthy, black South African gold miners (73).

$$\text{FVC (litres)} = 4.655H - 0.025A - 2.901$$

$$\text{FEV}_1 \text{ (litres)} = 3.665H - 0.030A - 1.654$$

H is height in metres and A is age in years. To compare the observed and predicted ventilatory function levels, we used the percentage of predicted values (the ratio of observed to predicted values times 100) for FVC (FVC%) and for FEV<sub>1</sub> (FEV<sub>1</sub>%). The ratio of FEV<sub>1</sub>/FVC <0.7 and predicted FEV<sub>1</sub>% <80% were used as indicators of airflow limitation according to the update of the WHO/GOLD criteria (74, 75).

### *Exposure assessment*

#### Dust exposure

Personal dust exposure was sampled during the day shift, which normally lasted about 5 to 10 hours. Five full-shift samples were taken on each monitoring day. Personal respirable dust was sampled using a SKC Sidekick pump (model 224-50) with a flow rate of 2.2 l · min<sup>-1</sup>. A rotameter was used to adjust the flow. The respirable dust samples were collected on 37-mm cellulose acetate filters (pore size 0.8 µm) placed in a 37-mm conductive plastic cyclone. The cassette was assembled and labelled at X-lab in Bergen, Norway. 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 limit of detection of 0.01 mg · m<sup>-3</sup>. Respirable dust samples were

analysed for quartz by X-ray diffraction on a silver membrane filter using the US National Institute for Occupational Health and Safety method 7500 at SGAB Analytica Laboratory, Luleå, Sweden. The limit of detection was  $0.005 \text{ mg} \cdot \text{m}^{-3}$ .

The individual cumulative exposure values to respirable dust or quartz ( $\text{mg} \cdot \text{year} \cdot \text{m}^{-3}$ ) for the 299 workers who participated in the study were estimated (Paper II).

### Gas exposure

Personal exposure to  $\text{NO}_2$ ,  $\text{NH}_3$  and CO was measured for a full shift using electrochemical sensors (Dräger PAC III) and passively by Dräger detector tubes. A study of tunnel construction workers in Norway used a similar method (76). They were attached at the collar of the worker to capture the gas concentration in the breathing zone.

For the Dräger tubes, the measurement ranges were 1.3 to 25 ppm for  $\text{NO}_2$  (Dräger tube: 8101111; standard deviation (SD)  $\pm 20\text{--}25\%$ ), 2.5 to 200 ppm for  $\text{NH}_3$  (Dräger tube: 8101301) and 6 to 75 ppm for CO (Dräger tube: 6733191).  $\text{SO}_2$  was also monitored with Dräger tubes (Dräger tube: 8101091; measurement range 0.7 to 19 ppm). Eight Dräger tubes were used daily: 4 for  $\text{NO}_2$ , 2 for CO and 2 for  $\text{NH}_3$ . The sampling time ranged from 5 to 10 hours.

### Processing of exposure data

The exposure data were close to log-normally distributed and were log-transformed for statistical analysis (77, 78). 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 two (79).

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, provided information about the ranges of exposure experienced between workers and from day to day (within workers) and were estimated as described by Rappaport (80):

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

The estimated, worker-specific mean exposure in job team  $h$  ( $\mu_{x,h(i)}$ ) was calculated as described by Rappaport et al. (81):

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

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

The individual cumulative exposure values ( $CE_i$ ) to respirable dust or quartz ( $\text{mg} \cdot \text{year} \cdot \text{m}^{-3}$ ) for the 299 workers who participated in a subsequent study on respiratory health effects were calculated analogously to Seixas et al. (82, 83):

$$CE_i = \sum (\mu_{x,h(i)})(t_{h(i)})$$

Where  $CE_i$  = estimated cumulative respirable dust or quartz in  $\text{mg} \cdot \text{year} \cdot \text{m}^{-3}$  for worker  $i$ .

$t_{h(i)}$  = number of years worker  $i$  has spent in job team  $h$

## ***Statistical analysis***

Data were analysed using SPSS version 12 (Papers I–IV). Table 2 summarizes the main statistical methods used for the studies. Continuous variables were described by arithmetic mean (AM) and geometric mean (GM). Categorical variables were described by number (%).

Categorical variables were compared across groups with the Pearson chi-square test (Papers III and IV). The independent *t*-test was used to compare continuous variables between high- and low-exposure groups (Paper IV).

Analysis of variance (ANOVA) was used on  $\log_e$ -transformed data to compare the mean respirable dust and quartz exposure between groups (Paper I). ANOVA and the post hoc Bonferroni test were also used to test differences in the mean lung function parameters between the groups (Paper III).

Multiple linear regression models were chosen for analysing the determinants of respirable dust and quartz exposure (Paper I). Multiple linear regression models were also used for testing the relationships between FEV<sub>1</sub>, FVC and FEV<sub>1</sub>/FVC and the cumulative dust or cumulative quartz exposure while adjusting for age, height and ever smoking (Paper III).

Pearson correlation coefficients were calculated for estimating the correlation between acute and chronic symptoms (Paper IV).

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 (84)(Paper II).

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 ( $_{ww}S^2$ ) (85) for respirable dust and quartz (Paper II).

Logistic regression models were used to determine odds ratios for  $FEV_1/FVC < 0.7$  and for  $FEV_1\% < 80$  for different categories of workers related to cumulative dust or quartz exposure while controlling for age, height and ever smoking (Paper III). Logistic regression analysis was also used to determine differences in respiratory symptoms between groups based on quartiles and the highest deciles of cumulative exposure groups using the lowest quartile as the reference group while controlling for ever-smoking and age (Paper IV).

**Table 2. Statistical methods used in the analysis**

<b>Paper</b>	<b>I</b>	<b>II</b>	<b>III</b>	<b>IV</b>
Mean (SD)	√	√	√	√
Frequencies and proportion	√		√	√
Chi-square			√	√
ANOVA	√	√	√	√
Linear multiple regression	√		√	√
Pearson correlation			√	√
Logistic regression			√	√
One-way random analysis		√		
Two-way random analysis		√		

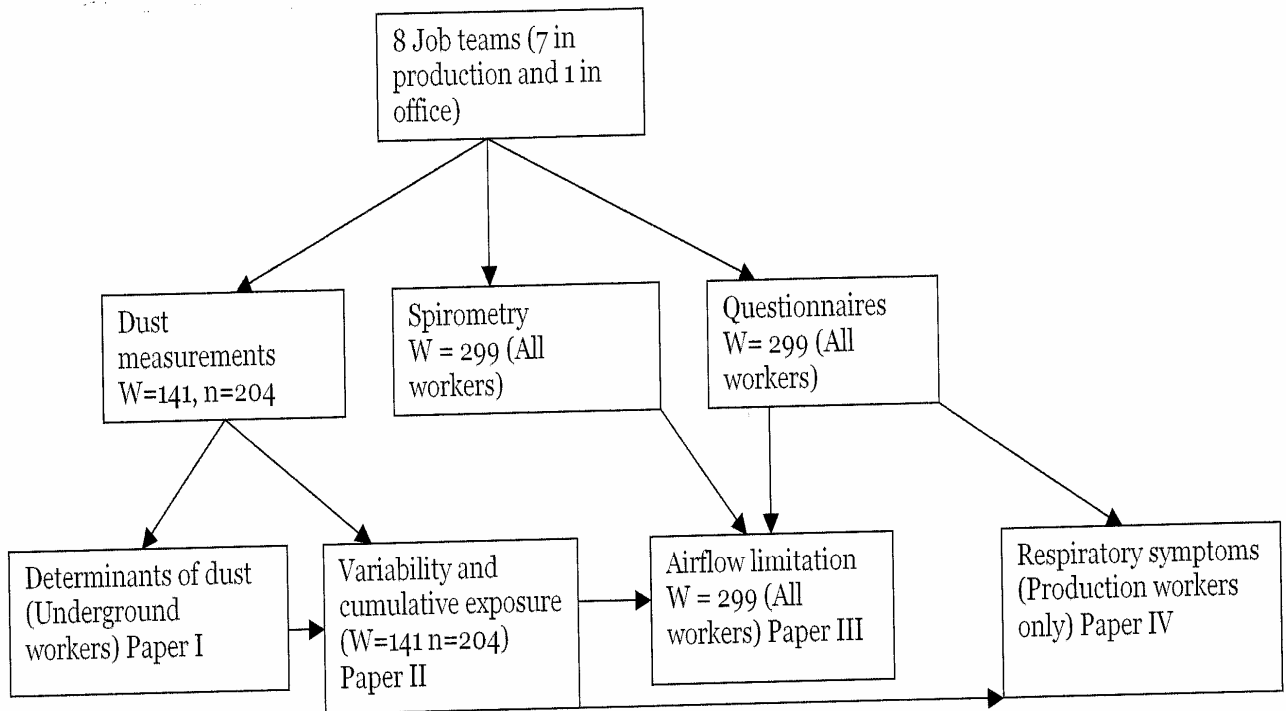


Fig 11. Link between papers in the study

## ***Synopses of papers***

### **Paper I**

Paper I described the personal exposure to respirable dust and quartz and identified important determinants of exposure in a labour-intensive coal mine. The respirable dust samples from randomly selected underground workers ( $n = 134$ ) were quantified by gravimetric analysis using a Mettler AT 261 delta range. The development team had the highest exposure to respirable dust and quartz (GM 1.80 and 0.073 mg · m<sup>-3</sup>). In this team, 55% of the respirable dust samples exceeded the threshold limit value (TLV) of 0.9 mg · m<sup>-3</sup> (86). The underground transport team was the least exposed, with no samples exceeding the TLV. The quartz content of the respirable dust for the underground job teams ranged from 3.9% to 8.7%. In development, the exposure to respirable dust and quartz was highest during drilling (GM 17.37 mg · m<sup>-3</sup> and 0.611 mg · m<sup>-3</sup>). In development, the highest percentages of respirable dust and quartz samples above the TLV of 0.05 mg · m<sup>-3</sup> (86) were during drilling (100% and 94%, respectively) and blasting (83% and 67%).

Statistical modelling of exposure to respirable dust and quartz in the development team indicated that pneumatic drilling and blasting were the most important determinants for increasing the respirable dust and quartz levels. The variables in multiple regression models for the development team workers explained 45.2% and 40.7% of the variance of the respirable dust and quartz exposure.

The regression model for quartz exposure in the development team predicts that drilling for more than 8.0% of the full shift of 8 hours will exceed the TLV of 0.05. For the



median time of pneumatic drilling in the present study (27.9%), the workers would be exposed to  $0.34 \text{ mg} \cdot \text{m}^{-3}$ , which is about 6.8 times higher than the TLV for quartz.

## **Paper II**

This paper reported the estimated variability in exposure to respirable dust and assessed 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. The geometric mean exposure to respirable dust and quartz was calculated for the 8 *a priori* groups, including the development team (1.80 and  $0.073 \text{ mg} \cdot \text{m}^{-3}$ , respectively), mine team ( $0.47$  and  $0.013 \text{ mg} \cdot \text{m}^{-3}$ ), transport team ( $0.14$  and  $0.006 \text{ mg} \cdot \text{m}^{-3}$ ) maintenance team ( $0.58$  and  $0.016 \text{ mg} \cdot \text{m}^{-3}$ ), washing plant ( $0.41$  and  $0.011 \text{ mg} \cdot \text{m}^{-3}$ ), boiler and turbine ( $0.31$  and  $0.020 \text{ mg} \cdot \text{m}^{-3}$ ), ash and cinder ( $0.73$  and  $0.020 \text{ mg} \cdot \text{m}^{-3}$ ) and office ( $0.07$  and  $0.006 \text{ mg} \cdot \text{m}^{-3}$ ).

The within-worker variance component was considerably higher than the between-worker variance component for most job teams. 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 to 22.5 in the 8 job teams, while the analogous within-worker distribution varied between 2.2 and 3902. 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.

Based on results from a two-way random model, which assumes common variance across the groups, the attenuation of the exposure–response curves was estimated to be 5.7% for respirable dust and 17.7% for quartz.

The estimated worker-specific mean exposure ranged from 0.07 mg · m<sup>-3</sup> among office workers to 18.17 mg · m<sup>-3</sup> among hard rock workers for respirable dust and from 0.007 mg · m<sup>-3</sup> to 0.889 mg · m<sup>-3</sup> for quartz. 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 (AM 10.2). The mean age of these workers was 37.0 years (range 20.5–57.6 years). Based on the worker-specific mean exposure, the estimated mean cumulative exposure for these workers was 38.1 (SD 78.5) mg · year · m<sup>-3</sup> for respirable dust and 2.0 (SD 3.8) mg · year · m<sup>-3</sup> for quartz. The estimated median cumulative exposure was 7.0 mg · year · m<sup>-3</sup> for respirable dust and 0.3 mg · year · m<sup>-3</sup> for quartz. The distribution of estimated cumulative exposure indicated that 10% of the workers had cumulative exposure higher than 109.0 mg · year · m<sup>-3</sup> for respirable dust and 5.3 mg · year · m<sup>-3</sup> for quartz.

### **Paper III**

Paper III described the relationship between cumulative respirable dust and quartz exposure and lung functioning among workers in a labour-intensive coal mine. The mean values of FVC and FEV<sub>1</sub> for the total study population were 4.29 litres (range 2.30–5.98), and 3.25 litres (range 1.36–4.81), respectively. The lowest mean values for FVC and FEV<sub>1</sub> were found among office workers. For the individual workers the FEV<sub>1</sub>/FVC ratios ranged from 0.56 to 0.93 (mean 0.76). There were no significant

differences between the job teams for the FVC, FEV<sub>1</sub> and FEV<sub>1</sub>/FVC. The mean prevalence of airflow limitation (FEV<sub>1</sub>/FVC <0.7) for all workers was 17.3%, with the highest prevalence in underground transport (31.0%), development (22.7%), underground maintenance (19.4%) and office (16.3%). The mean prevalence of FEV<sub>1</sub>% <80% among all workers was 10.8%, with the highest prevalence in development (20.5%), followed by office (11.6%) and ash and cinders (11.1%). The lowest mean value of the percentage predicted FEV<sub>1</sub> was found in development (94.6%).

Cumulative respirable dust exposure was correlated with FEV<sub>1</sub> ( $P = 0.04$ ) and the ratio of FEV<sub>1</sub>/FVC ( $P = 0.0001$ ). In multiple linear regression models, cumulative dust and quartz levels were nonsignificantly associated with decreases of 1 ml and 16 ml per  $\text{mg} \cdot \text{year} \cdot \text{m}^{-3}$  in FEV<sub>1</sub>, respectively, when controlling for age, height and ever smoking.

FEV<sub>1</sub>/FVC was significantly correlated with cumulative dust and quartz ( $-0.015\%$  per  $\text{mg} \cdot \text{year} \cdot \text{m}^{-3}$  and  $-0.3\%$  per  $\text{mg} \cdot \text{year} \cdot \text{m}^{-3}$ , respectively) while controlling for age, height and ever smoking. These models explained 8.4% of the total variance of FEV<sub>1</sub>/FVC.

The prevalence of FEV<sub>1</sub>/FVC <0.7 (43.5%) and FEV<sub>1</sub>% <80% (18.2%) was significantly higher among workers in the upper deciles of cumulative exposure to dust than among workers in the first quartile (reference group). In the logistic regression model, the highest 10% of the workers ranked by cumulative dust had significantly higher odds ratios for FEV<sub>1</sub>/FVC <0.7 (OR 4.36) than the reference group. The odds ratios for FEV<sub>1</sub>% <80% among the workers in the highest decile of exposure were significantly higher for both respirable dust and quartz (OR = 10.38 and 14.18, respectively). Workers

with FEV<sub>1</sub>/FVC <0.7 had experienced higher cumulative dust exposure ( $P = 0.04$ ), were older ( $P = 0.03$ ) and had a longer duration of employment ( $P = 0.03$ ) than those without such airflow limitation.

#### **Paper IV**

The development workers differed from workers from the other production teams for the symptoms breathlessness ( $P = 0.003$ ) and blocked nose ( $P = 0.03$ ). The prevalence of dry cough and running nose was also higher among development workers than other production workers, but these findings were not significant.

The odds ratios for reported acute breathlessness (2.96; 95% CI 1.44–6.11) and blocked nose (2.47, 95% CI 1.10–5.56) were significantly higher among development workers than among other production workers after adjusting for age and ever-smoking.

Workers in the development team had a significantly higher prevalence of breathlessness when walking with people of their own age than did workers from other job teams ( $P = 0.001$ ). The development workers also had a higher prevalence of all the other reported chronic respiratory symptoms than other workers, but these findings were not statistically significant.

Workers in the highest decile of cumulative exposure to respirable dust and quartz had significantly higher odds ratios for cough than the reference. In addition, the odds ratios for cough increased with increasing quartiles of the exposure groups. This suggests an exposure–response relationship between cumulative dust exposure and respiratory symptoms.

## ***Discussion***

### **Methodological considerations**

#### *Study design*

These cross-sectional studies cannot confirm a causal relationship between respirable dust and quartz exposure in a coal mine and respiratory health effects, but the statistical analysis performed helps us in this evaluation. We reported high prevalence rates of airflow limitation (Paper III) and of chronic respiratory symptoms (Paper IV) among workers with the highest cumulative respirable dust and quartz exposure and a higher prevalence of acute respiratory symptoms in the groups with the highest exposure. The exposure–response relationship between cumulative respirable dust and quartz exposure and the ratio of FEV<sub>1</sub>/FVC (Paper III) as well as chronic symptoms (Paper IV) indicate that mixed coal dust contributes significantly to the respiratory health effects.

#### *Validity*

Several factors might bias the validity of the observed relationship between exposure to mixed coal mine dust, airflow limitation and respiratory symptoms. Both internal and external validity should be taken into account. The internal validity refers to the inference drawn for the study subject. External validity refers to inferences related to the people outside the study population.

#### *Internal validity*

### Participation rate

The participation rate in this study was high, thus minimizing any threat to the validity of the data due to a low nonparticipation rate. The reason for the high participation rate might be the fact that the objective of the study was explained explicitly to workers. Since this was the first time dust exposure and respiratory health effects had been examined in the mine, the workers might also have been motivated to participate based on principle.

### Selection bias

Selection bias refers to the error that might arise due to systematic differences between those included and those not included. The most common selection bias in occupational epidemiology is the healthy-worker effect (87, 88). This may be divided into two: primary and secondary. The secondary healthy worker effect refers to an overrepresentation of healthy workers in the exposed groups, whereas sick workers have left for health reasons. This effect might have been present here, since the study population comprised only the workers who were available at the time of the study. This might contribute to reducing the measurable effects of respirable dust and quartz, as the status of those who had left the mine before the study for various reasons, including health reasons, were not represented.

The generally higher lung functioning among the production workers than among the office workers could also be explained by a primary healthy worker effect (or selection), as the production workers must be physically fit to qualify for the mining jobs at the

employment stage and to survive in strenuous and dust-exposed jobs. Office workers do not face such demands.

#### Information bias

The definition of acute symptoms might confuse workers with chronic symptoms. This may imply either that workers with chronic symptoms might also experience more acute symptoms or that workers with chronic symptoms report the problem as an acute symptom, thus exaggerating the acute respiratory problems among coal mine workers. Acute and chronic symptoms were correlated in this study (Paper IV), and this means that the results must be interpreted with caution.

#### Recall bias

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 shortages of explosives, market problems or problems with the washing plant, all of which may have contributed to overestimating the workers' period in the mine and overestimated cumulative exposure.

In this study, ex-smokers could not recall the numbers of cigarettes smoked, and thus the number of pack-years could not be quantitatively estimated.

#### *External validity*

This dissertation is based on the findings in a labour-intensive coal mine in a developing country. The mine still uses the old, traditional methods of harvesting coal. However, the exposure levels in our study were relatively similar to those from studies in

industrialized countries before dust control laws and regulations were enacted (11, 15, 89). Despite the differences in mining processes in industrialized and developing countries and the extensive manual work in the mine described here, the exposure–response relationships for airflow limitation were similar to the findings from industrialized countries (27, 59). However, our findings can probably best be generalized to coal mines in developing countries today, which utilize labour-intensive mining techniques by similar mining methods.

### *Confounding*

The most significant confounder in respiratory health studies such as ours is cigarette smoking. Cigarette smoking was low in our study population compared with other studies and did not significantly differ between production job teams. Nevertheless, in linear multiple regression and in logistic regression analysis, the exposure–response relationship between dust exposure and airflow limitation was controlled for smoking (Papers III and IV).

Other confounders in our studies were age, education level and duration of employment. Age was also controlled for in all exposure–response analysis, whereas education level was not considered since most workers in the mine had primary education only. Further, duration of employment was not controlled in our studies since the exposure variable used (cumulative exposure) was constructed by using the history of past duration of employment and the current exposure. When the association between development and other production workers was analysed, it was controlled for age.



### *Statistical analysis*

We used multiple linear regression analysis in Paper I to establish the determinants of dust exposure among workers in different job teams. However, only the development and mine teams were examined for determinants due to the low number of dust samples in the other teams.

In Papers III and IV we assumed that there are linear relationships between dust exposure and the airway limitation and respiratory symptoms. Through multiple logistic regression analysis, we noted that such relationships persist only for the highest quartile and decile of cumulative exposure. These analyses were chosen to be able to adjust for different factors and to evaluate a possible dose–response relationship.

### *Questionnaires*

The questionnaire was used as a standardized interview to obtain information on the sociodemographic characteristics, work history, smoking habits and respiratory symptoms. To avoid interviewer bias, only the investigator and a well-trained research assistant administered the questionnaire.

The questionnaire was translated into Swahili, the national language of Tanzania, back-translated into English and then pretested among a group of coal miners to ensure that the workers could understand it.

### *Pulmonary function testing*

Assessment of the FEV<sub>1</sub>, FVC and ratio of FEV<sub>1</sub>/FVC are commonly used as measures of ventilatory function in similar studies (90-94). In Paper III, we used the ventilatory indices in accordance with the guidelines and recommendations of the American Thoracic Society for detecting impaired lung functioning (72). Individual effort is needed to properly exhale into the spirometer to achieve acceptable ventilatory curves. The current study yielded few unacceptable spirograms because we conducted prior training and workers were cooperative.

The study used reference values from the regression equations for healthy, black South African gold miners (73). The study did not use the available reference equation for Tanzania by Mustafa because the population used mostly comprised students and workers from the faculty of medicine and a few police officers and municipal workers from Dar es Salaam (95) and is thus not considered to be representative for the workers in the coal mines.

### *Exposure assessment*

The overall representativeness of the measurements with relatively low number and few repeated samples in the some job teams might be questioned. This might be associated with bias in estimating the worker-specific mean exposure used in calculating cumulative exposure.

The workers were assigned a single group mean value although the exposure level was not homogeneous within all job teams. Thus, some low-exposure workers within a job

team might be overestimated, whereas high-exposure workers might be underestimated in the calculation of cumulative exposure.

The exposure measurement in this analysis did not distinguish between exposure intensity and duration, which is a major drawback for the cumulative exposure index (83, 96). The cumulative exposure estimated might not do well for quartz-related risk, where the high shift-team exposure is considered to be important (96-98).

The cumulative exposure was estimated based on constant exposure through years and on the assumption that the production was constant and no major rehabilitation took place.

## **Main discussion**

### *Occupational coal dust exposure*

Our study revealed that workers in the development team have the highest exposure to respirable dust (AM  $10.3 \text{ mg} \cdot \text{m}^{-3}$ ) and quartz (AM  $1.268 \text{ mg} \cdot \text{m}^{-3}$ ) in the labour-intensive coal mine. Higher quartz content above 5% was noted from the respirable dust samples taken from development workers who were drilling (9.3%) and blasting (8.7%) (Paper I). This finding suggests a higher risk of silicosis among these workers compared with others (7, 45, 99). For drilling in development, all respirable dust samples were above the TLV of  $0.9 \text{ mg} \cdot \text{m}^{-3}$  (86), whereas 94% of the quartz samples had concentrations above the TLV ( $0.05 \text{ mg} \cdot \text{m}^{-3}$ ). The high concentration levels in the

development team might be caused by lack of proper dust control measures during drilling and blasting. Further, only 14.1% of the eligible workers used a respiratory mask. The respirable dust and quartz exposure in this study was higher than that in the United Kingdom (100), the United States (12, 15, 82) and Australia (14). In Great Britain, rigorous dust sampling took place after the UK Pneumoconiosis Field Research, which regularly conducted gravimetric dust sampling (101).

### *Exposure variability*

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. Even though the day-to-day variability in exposure was very high, the eight job teams had relatively small differences in between-worker exposure (Paper II).

In the development section, the  $w_w R_{0.95}$  values indicate that the respirable dust and quartz exposure may vary from day to day by factors of 3902 and 9996, respectively (Paper II). Various tasks such as drilling, blasting, lashing and roofing are associated with large differences in exposure (Paper I). The time spent on such intermittent working processes and the rotation between these tasks are presumably the main explanations for the high day-to-day variability. An unpredictable geological environment in which the rock structures can differ from site to site might also partly cause this spatial variability. The high within-worker variance component in the underground maintenance team might be due to 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. This study did not consider an alternative grouping by job task.

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.

Our tertiles for cumulative respirable dust exposure of 2.8 and 18.4 mg · year · m<sup>-3</sup> 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<sup>-3</sup>), with the average years of exposure ranging from 3.3 to 10 for the worker groups included (17). The mean cumulative respirable dust exposure (38.1 mg · year · m<sup>-3</sup>) in our study was higher than estimated in a national study of pneumoconiosis among 1270 coal miners in the United States (15.5 mg · year · m<sup>-3</sup>) (82), 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.

#### *Dust exposure and lung functioning*

Cumulative exposure to respirable coal mine dust and quartz was significantly associated with airflow limitation, as indicated by an FEV<sub>1</sub>/FVC ratio of less than 0.7. The upper 10% of the workers ranked by cumulative dust exposure had a significantly

higher odds ratio for airflow limitation than the reference group. Further, workers with airflow limitation had significantly higher cumulative dust exposure and had longer duration of employment than those without airflow limitation.

The mean cumulative dust exposure for the seven job teams of production workers was 1.8–68 times higher than for office workers, and we expected these differences in exposure to result in differential effects on lung functioning. The lung functioning values of FEV<sub>1</sub> and FVC were lower among office workers than among production workers. These findings might partly be explained by the higher prevalence of smoking among the office workers compared with most other job teams and also the healthy worker effect. However, the overall prevalence of smoking among the study population was low compared with other studies elsewhere (51, 52, 59, 60, 102, 103) and should not have had a great impact.

Similar to most other exposure–response studies of coal miners (27, 32, 54, 57, 87, 104), office workers were not included in the analysis of the associations between dust exposure and lung functioning.

Our estimated effect of respirable dust on the ratio of FEV<sub>1</sub>/FVC was –0.015% per mg · year · m<sup>-3</sup>, which is very similar to the –0.017% per mg · year · m<sup>-3</sup> found in round 1 of the National Study on Coal Workers' Pneumoconiosis (57), –0.0775% per mg · year · m<sup>-3</sup> reported by Seixas et al. (59) and 0.0128% per mg · year · m<sup>-3</sup> reported by Attfield & Hodous (45).

In our multiple regression, the loss of FEV<sub>1</sub> was nonsignificantly related to cumulative dust and quartz exposure. The estimated effect of dust exposure on FEV<sub>1</sub> was –1.0 ml per (mg · year · m<sup>-3</sup>), and quite similar to the values in round 1 of the National Study on Coal Workers' Pneumoconiosis (57) (–0.5 ml per (mg · year · m<sup>-3</sup>)) and in a study in South Africa (105) (–1.1 ml per (mg · year · m<sup>-3</sup>)). Thus, the results from this labour-intensive mine appear to be relatively similar to those from previous studies from presumably more mechanized mines.

The logistic regression supported an exposure–response relationship between cumulative respirable dust and quartz and airway limitation; the odds ratios for FEV<sub>1</sub>/FVC <0.7 and FEV<sub>1</sub>% <80% were significantly higher for the workers within the highest decile of cumulative exposure.

#### *Dust exposure and respiratory symptoms*

Our study showed that workers in the development section were significantly affected by the acute symptoms of breathlessness and blocked nose compared with workers from other job teams. This might be explained by the higher exposure to respirable dust and quartz compared with other production workers in the mine (Paper I). This study also provides evidence indicating an association between the presence of chronic respiratory symptoms and exposure to quartz and respirable coal mine dust.

Our study showed a lower prevalence of reported chronic symptoms than in most other studies in the United Kingdom (27, 35, 37, 103), the United States (27, 53, 106), Sardinia, Italy (32) and China (60), which can be partly explained by the younger

population and lower prevalence of smokers in the present study than in previous studies.

Another concern is the possibility that other diseases than pneumoconiosis might account for our findings. This concerns especially infectious diseases. The numbers of people with tuberculosis has increased due to HIV infection in countries in sub-Saharan Africa (107, 108), including Tanzania. The estimated incidence of tuberculosis in Tanzania is 371 per 100,000 population, and the case detection rate in 2002 was 43% (109-111). We had a question on whether one worker had tuberculosis, but unless a worker is diagnosed by a physician, the worker would say no. That might reduce the strength of the exposure–response association. However, this problem was similar for all groups compared in this study.

### ***Study conclusions***

Workers in the coal mine had high exposure to respirable dust and quartz in relation to international limit values. The highest exposure was found among workers in the development team. Drilling and blasting operations were the major determinants of dust concentrations.

Workers in development and underground maintenance were exposed to high quartz content: above 5%.



High within-worker variability was noted, indicating high day-to-day variability in the exposure to both respirable dust and quartz, particularly for the development and underground maintenance workers.

This work has demonstrated an exposure–response relationship between exposure to coal mine dust and airway limitation as measured by FEV<sub>1</sub>/FVC and predicted FEV<sub>1</sub>%.

Workers in development had a higher prevalence of respiratory symptoms of cough and breathlessness than other production workers. There was an exposure–response relationship between cough and cumulative dust exposure.

### ***Recommendations for future research***

The data highlight several issues that merit investigation in future studies. A comprehensive longitudinal cohort study might reduce some uncertainties arising from this study due to the healthy worker effect. Such a prospective study design will better estimate both exposure and longitudinal lung functioning outcomes.

A research project to assess past exposure for different job categories in the respective sections of the mine should be developed. This will provide a more accurate estimate of historical exposure.

Routine health surveillance of workers is also needed to detect disease for early treatment, referral or appropriate placement of workers and to collect information for risk assessment and prevention purposes (112).

## ***Recommendations for preventive measures***

### **General recommendations**

Strategies to reduce exposure to respirable dust and quartz should be implemented including increased engineering control such as improved ventilation and ventilation design. Dust-wetting techniques during drilling might be important, and rigorous maintenance should be given priority to ensure that such techniques are in operation at all times.

Health and safety education campaign for coal miners should be initiated to focus on the hazards related to exposure to respirable coal dust and quartz, control measures and use of personal protective equipment (respiratory masks).

### **Specific work area–related recommendations**

In the development section, we recommend the sustainable continued use of water for drilling at all time of drilling, thus reducing the dust emitted to the air.

We also recommend the use of a rubber “skirt” placed around the drill rod to provide a containment barrier between the dust and worker.

Proper ventilation to the development section will also dilute the environmental dust intensity surrounding the miner.

The most highly exposed workers should be provided with half-mask respirators with at least filter type P2.

In the mining face, workers are recommended to wear a face mask during drilling and blasting and lashing of coal.

Workers in the underground maintenance section should adhere to all safety recommendations observed by development workers when working in the development section.

In the underground transport section, despite the lower levels of dust in this section, we recommend the use of a face mask when loading coal from bunker to the wagon, operating the underground locomotive and lashing coal from railway lines.

In the washing plant, dust concentrations were high in the tippler house and during crushing and screening, and workers in these sections are therefore strongly recommended to use a face mask. The revival of the water-spraying unit at the washing plant will reduce dust emissions from crushing and screening of coal.

In the ash and cinders section, we recommend that workers use respiratory face masks with filter type P2 as they handle ash and cinders. Cinders, which is burned coal,

contains some quartz. Maintenance of leaks in the duct may reduce the spread of ash and cinders to the environment.

In the boiler and turbine section, we recommend maintaining the conveyor to reduce the manual feeding of coal to the boiler and to reduce the dust emitted from the coal dropping out of the conveyor. We also recommend maintaining the ventilation fan to the area.

We also recommend the use of proper personal protection equipment for any other workers visiting the mine.

### ***Recommendations for policy measures***

Based on the findings, legal limits for exposure to respirable dust and quartz in coal mines in Tanzania need to be imposed and enforced.

A system of respiratory medical surveillance should be clearly outlined for miners through periodic standardized questionnaire surveys and annual spirometry. Such programmes are currently not practised in the mine.

A job exposure profile database for each worker should be established comprising information on employment in the mine, section, job and duration of employment. The developed system should be linked to dust sampling collected on a routine basis, and data should be archived in the industry.

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