



# Effect of Respirable Coal Mine Dust and Quartz on Lung Function Parameters of German Coalminers: A Longitudinal Study 1974-2004

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## Abstract

**Purpose:** Poorly soluble low toxic particulates (PSLT) and their particle specific effects on the respiratory system are under review in Europe. We aim to investigate the nature and magnitude of lung function deficits from coal and quartz exposure in coal miners.

**Methods:** Longitudinal inception cohort study (1974-2004) on miners who started working underground at two coal mines in Germany between 1974 and 1979. From the continuous exposure monitoring, the numbers of the shifts exposed and the shift-average concentration are available, so that long-term average and cumulative concentration of respirable coal dust and quartz component can be derived. The effects of exposure on lung function parameters (FVC, FEV<sub>1</sub>, FEV<sub>1</sub>/FVC) were estimated with generalized estimation equation (GEE) models, after adjusting for anthropometric factors, smoking behaviour, and lung function measuring devices.

**Results:** 14,940 lung function tests were performed for 1352 miners during 30 years of follow-up. On average, 11.1 lung function tests were available per miner. Compared to reference values, the averaged FVC, FEV<sub>1</sub>, FEV<sub>1</sub>/FVC varied from 95% to 103% at the end of follow-up. GEE-regression models indicated a negative impact of long-term average concentration of respirable quartz dust on FVC (-0.097l/0.1 mg/m<sup>3</sup>, p < 0.001), as well as on FEV<sub>1</sub> (-0.069 l/0.1 mg/m<sup>3</sup>, p = 0.003).

**Conclusions:** Negligible decline of lung function resulted from exposure to coal mine dust, while quartz dust concentration showed adverse effects.

## Keywords

Coal mine dust, Crystalline silica, Respiratory morbidity, Lung function, Retrospective cohort study, Inception cohort

## List of Abbreviations

PSLT: Poorly Soluble Low Toxic Particulates; FVC: Forced Vital Capacity; FEV<sub>1</sub>: Forced Expiratory Volume in 1 Second; FEV<sub>1</sub>/FVC: Ratio of Forced Expiratory Volume in 1 Second and Forced Vital Capacity; VC: Vital Capacity; GEE: Generalized Estimating Equation; COPD: Chronic Obstructive Pulmonary Disease; CWP: Coal Workers' Pneumoconiosis; RAG: Ruhr Coal Mine Aktiengesellschaft; BMI: Body Mass Index; L: Liter; GLI: Global Lung Function Initiative

## Introduction

Coal mining is amongst the most intensively investigated occupation with respect to dust exposure and health outcomes. The effects of coalmine dust exposure on human health have implication for an array of particles with similar chemical and physical property in respect to the risk assessment and the evaluation of preventive measures. Currently, poorly soluble low toxic particulates (PSLT), such as carbon black, titanium dioxide, and coalmine dust are again the focus of research since European regulation evaluates the

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particle-specific effect on chronic inflammation, and finally carcinogenicity.

For a long time, the risk of developing lung cancer or pneumoconiosis attributed to coal mine dusts was the major concern, which was extensively studied in United Kingdom, United States of America, and Germany [1-3]. However, additional respiratory diseases, from clinically relevant loss of lung function to chronic obstructive pulmonary disease (COPD), are additional potential hazard of occupational exposure. Longitudinal studies from the British miners [4,5] and the US American miners [6-8] have shown that coal miners suffer a decline in lung function associated with dust exposure.

Enhanced endeavor has been committed from coalmine industry to preventing respiratory diseases, in particular coal workers' pneumoconiosis (CWP), in Germany since decades. Regulations required a standardized medical examination program and document in relation to identified health hazards, i.e. either past or present dust exposure, within the workplace. Within Ruhr Coal Mine AG (RAG), the largest German coal mining company, a comprehensive health protection program is subject to corporate health protection and disease prevention commitments. All miners working underground must undergo a qualification examination at entry to exclude potential risk. During the occupational career, a continuous health surveillance program, including physical examination, lung function tests and chest posterior-anterior radiographs every two years, was provided to prevent developing coal workers' pneumoconiosis and to identify impairment of lung function.

In our previous report based on an inception cohort of RAG, no manifest CWP case was found after 30 years of follow-up [9]. The present study aims to study the risk of lung function impairment from a long-term exposure to coal mine dust, with a follow-up from 1974 through 2004.

## Material and Methods

### Study design and study population

This study was designed as a retrospective inception cohort study of coal miners working underground. It is a part of an extensive epidemiological study program, which was described more in detail regarding the definition of the cohort, dust measurement, and the collection of medical data including quality assurance [9-11]. Based on this inception cohort, the findings on lung function changes from a follow-up through 1998 [11] and the risk of developing CWP through 2004 [9] were published in previous reports. Here, results concerning the change of lung function from an extended follow-up through 2004 is reported in the present study. The present study is based on 1352 coal miners, who had at least one lung function test. Differences to the former report [9] in respect of coal worker's pneumoconiosis are due to the restriction to the miners with at least one lung function test.

The present analyses are based on an inception cohort consisting of 1352 newly hired coal miners between 1974 and 1979 without prior relevant exposure in two big collieries

in the Ruhr area (Heinrich Robertmine and Walsummine) of Germany. The cohort comprises 1369 coal miners (670 in Heinrich Robert and 699 in Walsum), thereof 1352 with lung function measurements. At Heinrich Robert colliery, high rank coking coal was mined which is used in steel production, while at Walsum colliery low rank gas and flaming coal was mined, which is used in energy production. Hence, this study population represents the typical stratigraphic horizons of the coal mined in the Ruhr area.

### Dust exposure

Coal mine dust is a mixture of different components due to the geological structure of coal seams. The present study focuses on total respirable coal mine dust and its respirable quartz dust component. RAG (the operator of the two investigated collieries) implemented measures for dust control from the mid-1950s. The dust measurements were carried out gravimetrically with the dust sampling device MPG II [12] reference measuring device that was installed in RAG collieries since 1974 [13]. Dust samples were analyzed by infrared spectroscopy to determine the quartz dust fraction. This made it possible to measure the precise coal mine dust load at a defined workplace as well as its quartz component.

The person-based dust exposure of the coal miners in the study was quantified according to an individual performance record since January 1, 1974. The documentation system of these performance records was adjusted several times during the study period but throughout information about medical examinations, duration and type of employment, fine dust concentrations in the operation and person-related dust exposure values are available. The last version was developed according to the Regulation on Health Protection in Mining [13,14]. These data were used in the shift steering system at RAG to control for the long-term exposure limit value defined by the authorities.

Based on the documentation system at RAG, in which the shift data and performance records were entered, the type, scope and place of employment, 8-h shift average dust concentration for each underground employee was available for the study period from 1974 to 2010. Individual data on the number of underground shifts and the annual average concentration of respirable dusts were extracted. Annual cumulative exposure is a function of the shift average concentration and the number of shifts performed.

### Lung function data

The mining regulation of the North Rhine-Westphalian Mining Inspectorate [15,16] and the Regulation on Health Protection in Mining [14] specified occupational health examinations for coal miners. Regulations required a standardized medical examination program and documentation in relation to identified health hazards. Regular physical examination, lung function tests and chest posterior-anterior radiographs every two years, were provided to identify impairment of lung function and to prevent the development of coal workers' pneumoconiosis.

Spirometry has been the standard method to examine the

lung function. During the study period from 1974 to 2010, four different devices for lung function measurements were used.

- Bell spirometry [17]
- Wedge Type Spirometer Vitalograph [18,19]
- Oscillo-resistometer/spirometer CustoVit [20,21]
- Jäger's body plethysmograph [22,23]

The use of various devices was recorded longitudinally. The changes of staff members in a lung function measuring team at the Heinrich Robert mine was also documented as a potential influencing factor. For assuring the comparability of the measurements within a measurement team, internal trainings (separately in the two mines) and regular department meetings were organized. The spirometric devices were calibrated on a daily basis. Since approximately 1990, body plethysmographs have been introduced, with additional support of computer for the purpose of quality control. Before the spirometric data was entered into our data set, a team of trained occupational health physicians reviewed the data and categorized each measurement to one of four categories (not usable/normal finding/borderline pathological finding/pathological finding). For discrepancy of the review results, a consensus was reached among the participating physicians according to the criteria. Thus, each categorization represents an expert decision. Furthermore, plausibility of the data were checked with programs. Any non-plausible findings were reviewed timely by the physicians [10].

A total of 14,940 lung function tests were performed for the study population. When using bell spirometry, only vital capacity (VC) could be measured. Sub-group analyses including 14,062 lung function tests, after excluding the 878 measurements using the bell spirometry, are reported with respect to lung function profiles. The following lung function parameters were selected for the analyses [21]:

- Maximal value of vital capacity ( $VC_{max}$ ): Maximum of either forced vital capacity (FVC) or in the case of measurement with a dry spirometer, the vital capacity (VC) measured in liter (L).
- Forced expiratory volume in 1 second ( $FEV_1$ ): Measured in L.
- Relative capacity in 1 second, the ratio calculated from forced expiratory volume in 1 s and forced vital capacity ( $FEV_1\%VC_{max}$ ), measured in percentage (%).

The individual decline of lung function parameters was assessed in a longitudinal manner. In addition, the most recent available lung function measurement was compared to the reference value in a cross-sectional manner.

## Data on confounding factors

The basic anthropometric data of body weight and height, and information on smoking behavior were collected from all study participants. Data on smoking status and pack-years are based on self-report of the miners during the medical examinations. Missing data for smoking were imputed

according to the rule of "last observation was carrying forward" for the years without an examination. The miners are classified into active smokers, former smokers, and never smokers. Two different coal types, coking coal comparing to gas and flaming coal, from the involved coal mines was adjusted in the regression models. Thus, a potential clustering effect across the mines was considered.

## Statistical analyses

Two different reference values based on general population [24,25] are calculated based on gender, age, height, and nationality for each participant and year. In the cross-sectional analysis, we compare the last available examination of lung function parameters with these external reference values. Additionally, yearly and age-specific mean values of the measured and predicted values and of their quotients are calculated.

With respect to the changes of the lung function parameters over time, generalized estimating equations (GEE) models are used to estimate the effect of dust exposure. GEE models take the correlation between the repeated intra-individual measurements into account [26,27]. We applied an exchangeable working correlation matrix as an underlying correlation structure. The models are adjusted for the following potential confounding factors: height, weight, age, the lung function measuring device, year of measurement, nationality (German or other), smoking status, and cumulative pack-years. Age was additionally classified into two group ( $> 25$  years or  $\leq 25$  years), and entered separately into the model to account for the non-linear age effect on lung function parameters as described in Quanjer, et al. [24] and GLI [25]. Covariates were selected depending on their significance: all variables that had a significant effect ( $p \leq 0.05$ ) in at least one model (i.e. on one of the relevant lung function parameters and in one of the two approaches) were included into all GEE models in order to attain comparability of all models.

In order to estimate the effect of exposure to respirable coal mine dust or respirable quartz, two approaches are used: (i) Cumulative dust exposure; (ii) Long-term average dust exposure in combination with exposure duration were considered in the models, respectively in linear or logarithmic form.

All calculations were performed using the Stata Version 13 [28] statistics package. A statistical significance level of 5% is applied throughout our analyses.

## Results

Characteristics of the present inception cohort are summarized in Table 1a, restricted to the 1352 coal miners with lung function measurements after exposure onset. At the beginning of follow-up, the study subjects were in average 20.4 years old. Almost 31% and 68% of the miners have reported to be active and never smokers, respectively. The smoking status have changed during the follow-up, so that respectively 50%, 24%, and 26% of the miners reported to be active, former, and never smokers at the end of the follow-up.

**Table 1a:** Characteristics of the inception cohort, restricted to the 1352 coal miners with lung function measurements after exposure onset.

	N (%)	mean	sd	min	max
Age at entry to FU (yrs)	1352	20.4	5.0	14	50
Age at end of FU (yrs)	1352	40.1	8.6	16	60
Number of lung function measurements	1352	11.7	5.3	1	26
BMI at entry	1352	22.7	3.3	15.1	41.1
BMI at end of FU	1352	27.2	4.6	16.4	67.8
Smoking status and pack years at entry to FU					
Current smoker, N (%)	425 (31)	3.6	4.0	0.1	52
Former smoker, N (%)	4 (0.3)	5.9	5.1	3.0	13.5
Never smoker, N (%)	923 (68)	0	0	0	0
Smoking status and pack years at end of FU					
Current smoker, N (%)	675 (50)	15.9	10.2	0.1	52.5
Former smoker, N (%)	322 (24)	11.8	9.2	0.3	84.0
Never smoker, N (%)	355 (26)	0	0	0	0
Nationality					
German, N (%)	1168 (85)				
Other, N (%)	201 (15)				

FU: Follow-up; sd: Standard deviation; min: Minimum; max: Maximum.

**Table 1b:** Distribution of exposure metrics for respirable coal mine dust and quartz dust in this inception cohort of 1352 coal miners.

	median	mean	sd	min	max
<b>Respirable coalmine dust</b>					
Long-term average concentration (mg/m <sup>3</sup> )	2.34	2.47	0.65	0.84	4.51
Total duration (dust-years)	17.07	15.11	6.69	0.72	28.00
Total cumulative exposure (mg/m <sup>3</sup> -years)	37.00	37.41	19.67	1.13	100.15
<b>Respirable quartz dust</b>					
Long-term average concentration (mg/m <sup>3</sup> )	0.09	0.09	0.03	0.00	0.26
Total duration (quartz-years)	12.92	11.46	5.84	0.00	22.86
Total cumulative exposure (mg/m <sup>3</sup> -years)	0.99	1.05	0.67	0.00	3.76

## Dust exposure

Statistical measures of personal long-term average concentration, exposure duration, and cumulative exposure to respirable coalmine dust and respirable quartz component are summarized in [Table 1b](#). The average duration of exposure to respirable dust was 17.1 dust-years (where a dust-year is defined to be 220 shifts with dust exposure). The long-term average concentration of exposure to respirable coalmine dust and quartz was respectively 2.34 (sd = 0.65) and 0.09 (sd = 0.03) mg/m<sup>3</sup> at the end of exposure, while two individuals exceeded the exposure level of 4 mg/m<sup>3</sup>. The cumulative exposure to respirable coalmine dust and quartz was respectively 37.0 (sd = 19.7) and 0.99 (sd = 0.67) mg/m<sup>3</sup>-years on average.

Temporal trends of yearly average dust concentrations are demonstrated according to the coalmines and total cohort in [Figure 1](#), with comparison to the occupational exposure limit values over time. The average exposure level started from a low level at the beginning of the follow-up. A peak exposure

level below 4 mg/m<sup>3</sup> was observed in the mid 80's, followed by a steady downward trend with less volatility after 2000.

## Lung function

Totally, 14,940 lung function tests had been performed among the 1,352 study participants during an average of 19.6 years of follow-up, which is in accordance with a desired examination frequency of every two years for each miner. Different lung function measuring devices have been applied over the follow-up period. Among the total measurements, 6,913 (49%), 3,218 (30%), and 3,931 (26%) lung function tests were performed respectively with Vitalograph, Custo Vit, Body plethysmograph, while only 878 (6%) measurements were performed with bell spirometry from 1974 to 1978.

Results from the cross-sectional analyses of the last available lung function examination at the end of follow-up are summarized in [Table 2](#). Lung function parameters in relationship to the predicted values are presented respectively according to Quanjer, et al. [24] and Global Lung

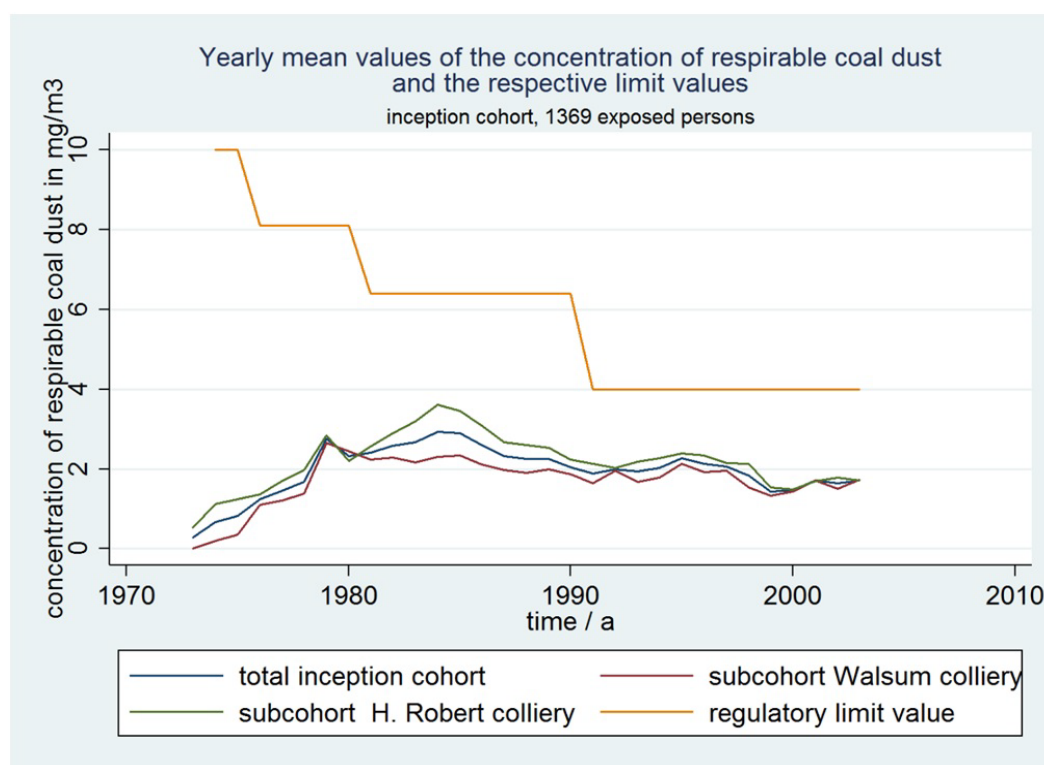


Figure 1: Temporal trends of yearly average dust concentrations over calendar time, comparing to the regulatory limit value at workplace.

Table 2: Cross-sectional analysis of lung function parameters, percentage of predicted value in reference to GLI and Quanjer equation, at the beginning (first available examination) [24,25] and at the end of follow-up (last available examination) of 1352 miners with measurements of FVC, and 1343 miners with measurements of FEV<sub>1</sub>.

Lung function parameters			mean	median	sd	min	max
FVC	At the beginning of FU	% GLI 2012	104.10	104.05	11.28	66.27	144.92
		% Quanjer 1993	108.07	107.82	11.85	67.99	148.75
		absolute values/liter	5.51	5.48	0.81	3.1	8.0
	At the end of FU	% GLI 2012	95.92	95.56	12.10	44.05	137.32
		% Quanjer 1993	103.15	102.66	13.03	46.72	146.92
		absolute values/liter	4.91	4.86	0.85	2.14	8.0
FEV <sub>1</sub>	At the beginning of FU	% GLI 2012	101.60	102.44	14.00	21.12	147.44
		% Quanjer 1993	105.56	106.33	14.62	21.89	155.80
		absolute values/liter	4.55	4.52	0.77	1.0	7.28
	At the end of FU	% GLI 2012	95.23	95.41	14.49	21.10	137.46
		% Quanjer 1993	100.48	100.85	15.38	21.88	146.69
		absolute values/liter	3.93	3.91	0.76	0.85	6.72
FEV <sub>1</sub> %FVC	At the beginning of FU	% GLI 2012	96.91	98.33	10.00	25.29	155.83
		% Quanjer 1993	100.20	101.56	10.42	26.28	160.03
		absolute values/%	82.72	83.84	8.67	21.74	100.00
	At the end of FU	% GLI 2012	98.81	100.34	9.46	37.45	125.54
		% Quanjer 1993	100.19	101.78	9.58	38.10	126.77
		absolute values/%	80.02	81.14	7.72	30.91	100.00

Function Initiative approach, GLI [25]. Based on GLI approach, the average relative lung function parameters, FEV<sub>1</sub>, VC<sub>max'</sub>

and FEV<sub>1</sub>/VC<sub>max'</sub> ranged from 95% to 99%, while the results based on Quanjer, et al. [24] approach were numerically

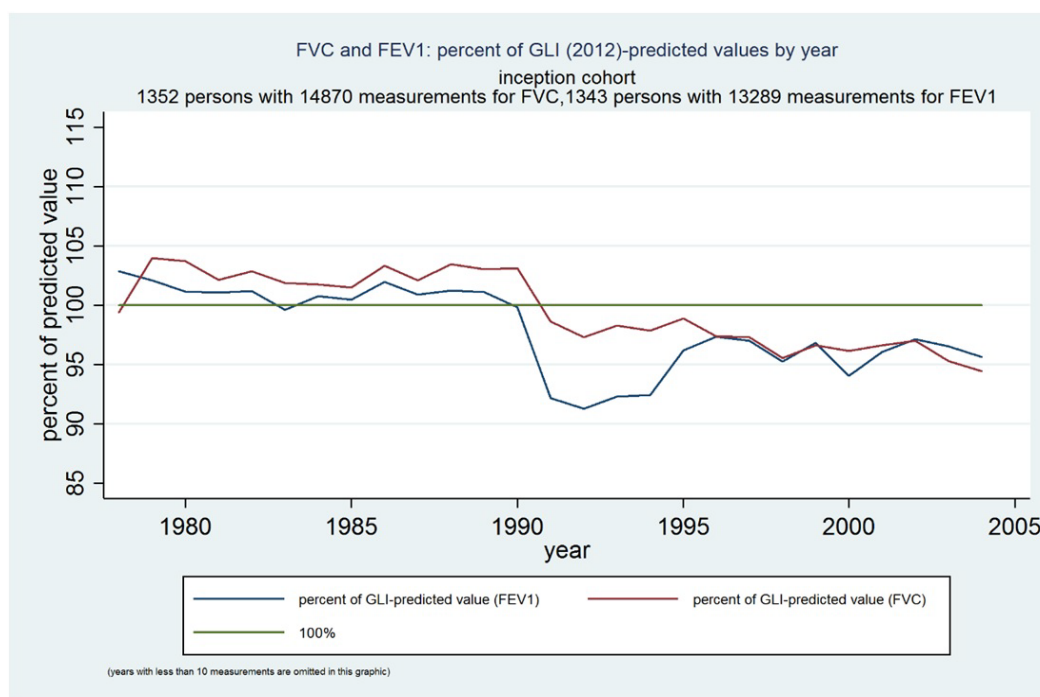


Figure 2a: FVC and FEV1 compared to GLI (2012) predicted values according to calendar years.

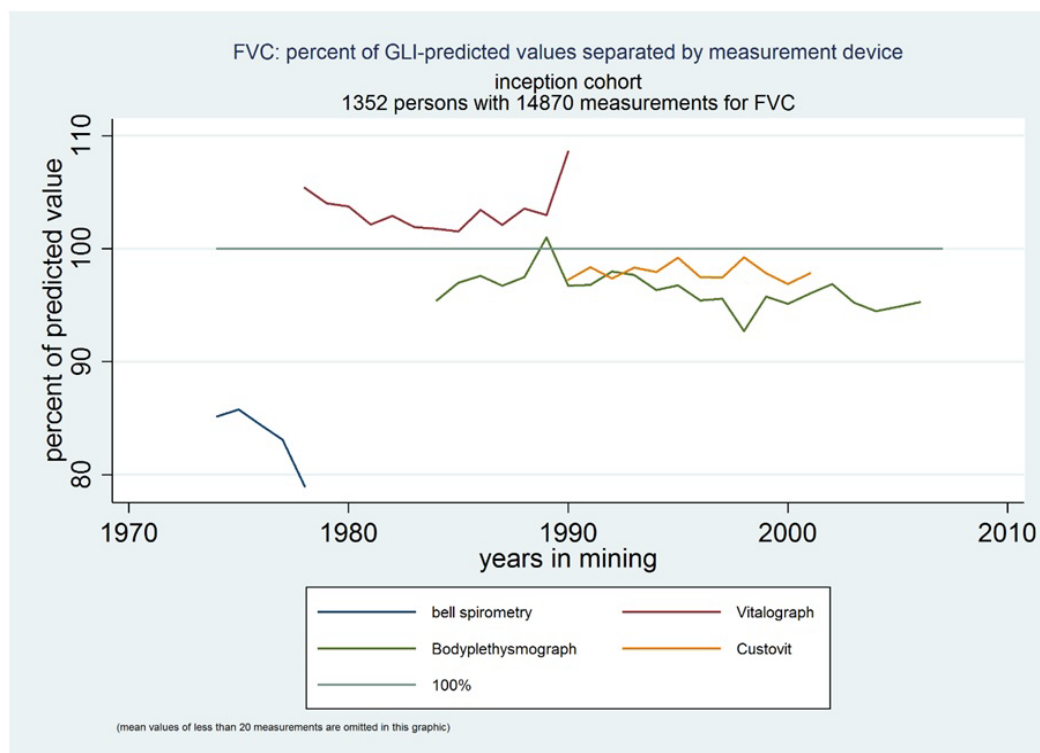


Figure 2b: FVC measurements, separated according to measurement device.

higher, ranging from 100% to 103%.

Figure 2a displays the course of the averaged quotients ( $FEV_1$  and  $VC_{max}$ ) according to the calendar years. In Figure 2b the same quotients are displayed separately by lung function measurement device, which demonstrates the pronounced influence of the measuring devices on the result.

In longitudinal analyses, the effects of dust exposure on the long-term change of lung function were estimated with GEE models. The linear function of exposure measures met better the assumption of normal distribution than the logarithmic transformed exposure measures; we focus the results handling exposure measures in a linear scale.

**Table 3a:** GEE model (Approach 1): Effect estimates for longitudinal change of lung function parameter sin relationship with cumulative exposure of coal mine dust (in mg/m<sup>3</sup>-years) and co. variables. No. of subjects = 1343.

Covariable	VC <sub>max</sub> (liters)			FEV <sub>1</sub> (liters)			FEV <sub>1</sub> /VC <sub>max</sub> (%)		
	Estimate	Std.Err	P >  z	Estimate	Std.Err	P >  z	Estimate	Std.Err	P >  z
<b>Approach 1</b>									
Cumulative coal mine dust*	-0.002	0.001	0.074	-0.001	0.001	0.505	0.010	0.011	0.389
Height (in cm)	0.063	0.002	< 0.001	0.049	0.002	< 0.001	-0.056	0.025	0.023
Weight (in kg)	-0.005	0.001	< 0.001	-0.005	0.001	< 0.001	-0.006	0.010	0.532
Age ≤ 25	-0.035	0.004	< 0.001	-0.034	0.003	< 0.001	-0.127	0.039	0.001
Age > 25	-0.029	0.004	< 0.001	-0.032	0.003	< 0.001	-0.195	0.037	< 0.001
Non-German nationality***	-0.161	0.045	< 0.001	-0.184	0.042	< 0.001	-1.277	0.494	0.010
Active smoker***	-0.145	0.022	< 0.001	-0.090	0.021	< 0.001	0.184	0.255	0.471
Former smoker***	-0.109	0.031	< 0.001	-0.021	0.028	0.458	0.908	0.346	0.009
Cumulative pack years	-0.004	0.001	0.004	-0.008	0.001	< 0.001	-0.096	0.016	< 0.001
Coking coal***	0.271	0.032	< 0.001	0.087	0.030	0.004	-2.461	0.355	< 0.001
Custovit***	0.128	0.012	< 0.001	-0.025	0.011	0.026	-2.480	0.170	< 0.001
Vitalograph***	0.358	0.023	< 0.001	0.390	0.023	< 0.001	1.173	0.314	< 0.001
Year of measurements	0.014	0.004	< 0.001	0.023	0.004	< 0.001	0.233	0.042	< 0.001

Statistics: Hazard ratio with standard error, Wald test: z-value, two-sided p-value; \*unit: In mg/m<sup>3</sup>-years; \*\*Reference: German nationality; gas and flaming coal; non-smoker; body plethysmograph.

**Table 3b:** GEE model (approach 2): Effect estimates for longitudinal change of lung function parameters in relationship with concentration (in mg/m<sup>3</sup>) and duration (in dust-years) of coal mine dust exposure and covariables. No. of subjects = 1343.

Covariable	VC <sub>max</sub> (liters)			FEV <sub>1</sub> (liters)			FEV <sub>1</sub> /VC <sub>max</sub> (%)		
	Estimate	Std.Err	P >  z	Estimate	Std.Err	P >  z	Estimate	Std.Err	P >  z
<b>Approach 2</b>									
Coal mine dust concentration*	0.012	0.013	0.370	0.014	0.014	0.329	0.108	0.186	0.563
Duration of exposure **	0.007	0.003	0.021	0.007	0.003	0.021	0.019	0.040	0.629
Height (in cm)	0.063	0.002	< 0.001	0.049	0.002	< 0.001	-0.057	0.025	0.023
Weight (in kg)	-0.005	0.001	< 0.001	-0.004	0.001	< 0.001	-0.006	0.010	0.532
Age ≤ 25	-0.037	0.004	< 0.001	-0.035	0.003	< 0.001	-0.126	0.039	0.001
Age > 25	-0.031	0.004	< 0.001	-0.034	0.003	< 0.001	-0.193	0.037	< 0.001
Non-German nationality***	-0.176	0.045	< 0.001	-0.195	0.042	< 0.001	-1.268	0.490	0.010
Active smoker***	-0.148	0.022	< 0.001	-0.092	0.021	< 0.001	0.202	0.252	0.424
Former smoker***	-0.109	0.030	< 0.001	-0.020	0.028	0.458	0.918	0.345	0.008
Cumulative packyears	-0.004	0.001	0.008	-0.007	0.001	< 0.001	-0.097	0.016	< 0.001
Coking coal***	0.247	0.031	< 0.001	0.069	0.030	0.021	-2.457	0.361	< 0.001
Custovit***	0.118	0.012	< 0.001	-0.032	0.011	0.004	-2.467	0.169	< 0.001
Vitalograph***	0.350	0.022	< 0.001	0.385	0.022	< 0.001	1.179	0.311	< 0.001
Year of measurements	0.008	0.004	0.047	0.019	0.004	< 0.001	0.236	0.044	< 0.001

Statistics: Hazard ratio with standard error, Wald test: z-value, two-sided p-value. \*unit: In mg/m<sup>3</sup>; \*\* unit: dust-years; \*\*\*Reference: German nationality; gas and flaming coal; non-smoker; body plethysmograph.

With approach 1, the effect of cumulative exposure to coal mine dust was estimated. Statistically significant effect was found with respect to VC<sub>max</sub> (-0.002 liter per mg/m<sup>3</sup>.years of coalmine dust, p = 0.074), while no significant effect on FEV<sub>1</sub> and FEV<sub>1</sub>/VC<sub>max</sub> was found (Table 3a).

With approach 2, long-term average concentration in combination with exposure duration, on a linear scale, were included at the same time in the regression models (Table 3b). Both long-term average concentration of coalmine dust and exposure duration showed a non-negative impact on VC<sub>max</sub>,

**Table 4a:** GEE model (approach 1): Effect estimates for longitudinal change of lung function parameters in relationship with cumulative exposure of quartz dust (in 0.1 mg/m<sup>3</sup>-years) and co-variables. No. of subjects = 1343.

Covariable	VC <sub>max</sub> (liters)			FEV <sub>1</sub> (liters)			FEV <sub>1</sub> /VC <sub>max</sub> (%)		
	Estimate	Std.Err	P >  z	Estimate	Std.Err	P >  z	Estimate	Std.Err	P >  z
<b>Approach 1</b>									
Cumulative quartz dust*	0.007	0.002	0.001	0.004	0.002	0.088	-0.034	0.026	0.192
Height (in cm)	0.063	0.002	< 0.001	0.049	0.002	< 0.001	-0.056	0.025	0.024
Weight (in kg)	-0.005	0.001	< 0.001	-0.005	0.001	< 0.001	-0.007	0.010	0.462
Age ≤ 25	-0.036	0.004	< 0.001	-0.034	0.003	< 0.001	-0.121	0.038	0.002
Age > 25	-0.030	0.003	< 0.001	-0.033	0.003	< 0.001	-0.187	0.036	< 0.001
Non-German nationality***	-0.178	0.045	< 0.001	-0.192	0.042	< 0.001	-1.183	0.488	0.015
Active smoker***	-0.145	0.022	< 0.001	-0.090	0.021	< 0.001	0.193	0.251	0.442
Former smoker***	-0.107	0.030	< 0.001	-0.020	0.028	0.468	0.909	0.344	0.008
Cumulative packyears	-0.004	0.001	0.007	-0.008	0.001	< 0.001	-0.098	0.016	< 0.001
Coking coal***	0.284	0.031	< 0.001	0.095	0.029	0.001	-2.502	0.338	< 0.001
Custovit***	0.125	0.012	< 0.001	-0.026	0.011	0.019	-2.458	0.167	< 0.001
Vitalograph***	0.363	0.023	< 0.001	0.393	0.023	< 0.001	1.154	0.313	< 0.001
Year of measurements	0.009	0.004	0.017	0.021	0.003	< 0.001	0.263	0.041	< 0.001

Statistics: Hazard ratio with standard error, Wald test: z-value, two-sided p-value. \*unit: In 0.1 mg/m<sup>3</sup>-years; \*\*Reference: German nationality; thermal coal; non-smoker; body plethysmograph.

**Table 4b:** GEE model (approach 2): Effect estimates for longitudinal change of lung function parameters in relationship with concentration (in 0.1 mg/m<sup>3</sup>) and duration (in quartz-years) of quartz dust exposure and co-variables. No. of subjects = 1343.

Covariable	VC <sub>max</sub> (liters)			FEV <sub>1</sub> (liters)			FEV <sub>1</sub> /VC <sub>max</sub> (%)		
	Estimate	Std.Err	P >  z	Estimate	Std.Err	P >  z	Estimate	Std.Err	P >  z
<b>Approach 2</b>									
Quartz dust concentration*	-0.097	0.023	< 0.001	-0.069	0.023	0.003	0.099	0.293	0.735
Duration of exposure **	0.000	0.003	0.897	-0.002	0.003	0.537	-0.039	0.039	0.324
Height (in cm)	0.063	0.002	< 0.001	0.049	0.002	< 0.001	-0.056	0.025	0.023
Weight (in kg)	-0.005	0.001	< 0.001	-0.005	0.001	< 0.001	-0.008	0.010	0.454
Age ≤ 25	-0.036	0.004	< 0.001	-0.034	0.003	< 0.001	-0.118	0.039	0.002
Age > 25	-0.029	0.004	< 0.001	-0.032	0.003	< 0.001	-0.186	0.036	< 0.001
Non-German nationality***	-0.162	0.045	< 0.001	-0.180	0.042	< 0.001	-1.197	0.487	0.014
Active smoker***	-0.134	0.022	< 0.001	-0.082	0.021	< 0.001	0.181	0.256	0.480
Former smoker***	-0.100	0.031	0.001	-0.015	0.028	0.584	0.903	0.347	0.009
Cumulative packyears	-0.004	0.001	0.003	-0.008	0.001	< 0.001	-0.098	0.016	< 0.001
Coking coal***	0.217	0.031	< 0.001	0.050	0.030	0.090	-2.398	0.342	< 0.001
Custovit***	0.133	0.012	< 0.001	-0.020	0.011	0.068	-2.475	0.167	< 0.001
Vitalograph***	0.370	0.023	< 0.001	0.397	0.023	< 0.001	1.115	0.318	< 0.001
Year of measurements	0.013	0.004	< 0.001	0.024	0.004	< 0.001	0.264	0.044	< 0.001

Statistics: Hazard ratio with standard error, Wald test: z-value, two-sided p-value. \*unit: In 0.1 mg/m<sup>3</sup>; \*\* unit: Quartz-years; \*\*\*Reference: German nationality; gas and flaming coal; non-smoker; body plethysmograph.

FEV<sub>1</sub>, and FEV<sub>1</sub>/VC<sub>max</sub> with no statistical significance. Declining lung function parameters were significantly associated with increasing age, both for the age groups below and over 25 years.

Analogously, the impact of respirable quartz dust were estimated with GEE models, respectively with approaches 1

and 2. Table 4a summarizes the risk estimates of cumulative exposure, which does not show a negative association with VC<sub>max</sub> and FEV<sub>1</sub>, as well as non-significant association with FEV<sub>1</sub>/VC<sub>max</sub>.

In contrast, long-term average concentration of respirable quartz dust showed statistically significant negative impact



on  $VC_{max}$  and  $FEV_1$ . Table 4b summaries the risk estimates with approach 2, every  $0.1 \text{ mg/m}^3$  increase of quartz dust concentration was indicated to be link with 0.097-liter loss of  $VC_{max}$ , as well as 0.069-liter loss of  $FEV_1$ .

## Discussion

We evaluated the relationship between exposure to coalmine dust containing quartz and long-term lung function loss in a German inception cohort of coal miners. As compared to external reference values, lung function of the participants was unexceptional at the end of follow-up. Although a qualitative assessment was not foreseen in the study plan, prevalence of an obstructive patten ( $FEV_1 / FVC < 70\%$  and  $FEV_1 < 80\%$  of predicted value) was elevated from 6.3% at the beginning to 9.0% at the end of the follow-up. GEE regression models were used to estimate the impact of exposure to respirable coal mine dust and its quartz fraction on lung function, after adjusting for biological aging effect and other relevant confounders. No statistically significant negative effect of exposure to coal mine dust on  $FEV_1$  and  $FEV_1/VC_{max}$  could be determined. Despite of marginally statistical non-significance, an estimate of  $-0.002$  liter per  $\text{mg/m}^3 \cdot \text{year}$  of coalmine dust on loss of  $VC_{max}$  would imply a loss of 75 ml of  $VC_{max}$  totally, provided an average cumulative exposure to coalmine dust of  $37.41 \text{ mg/m}^3 \cdot \text{years}$ . Meanwhile aging showed consistently negative impact on  $VC_{max}$  and  $FEV_1$ , would a decline of approximately 30 ml. The results from our models showed that even increments of age below 25 years have a negative impact on lung function, which is contrary to the normal age course of lung function. This could be resulted from a collinear relationship between age and cumulative exposure, and age appears to have captured largely the impact of exposure on lung.

Comparing the long-term average concentration ( $0.09 \text{ mg/m}^3$ ) with the current occupational exposure limit value (OEL) ( $0.05 \text{ mg/m}^3$ ) for quartz in Germany, loss of 44.5 ml on  $VC_{max}$  or 31.6 ml on  $FEV_1$  would be prevented if the OEL had been complied with during an average exposure of 11.46 quartz-years.

The relationship between coalmine dust and decline of lung function has been reported in numerous cross-sectional studies [5-7,29-32]. Since results from cross-sectional studies without considering temporal order have potential for bias, two longitudinal studies were conducted to address this relationship in the British and Australian cohorts [4,33]. The findings of this inception cohort study are not consistent with that from these cohorts. Apart from the methodological limitations of these studies, such as secondary selection and lack of statistical power, the magnitude of the dust exposure was much higher than that of the present cohort since the 70's. A straightforward comparison between the studies would be difficult [34].

Very few existing longitudinal studies involving repeated measurements provide an insight of profile of lung function over time. Two previous studies [8,35] reported an early impairment pattern observed in the US and the Chinese coal miners. In the US study, a rapid initial decline was indicated between two measuring points, comparing the FVC and  $FEV_1$

prior to and post the cross-sectional examination around 1972-1975, while no additional loss of lung function related to dust exposure could be detected during the following 15 years. The Chinese study reported a longitudinal observation of 15 repeated lung function tests within 36 months. A rapid decline of  $FEV_1$  of 0.12l was observed for those aged over 20 years during the first 12 months, while the impact of exposure to coal mine dust ( $-0.0002l$  per  $\text{mg/m}^3$ ,  $p = 0.3033$ ) was almost negligible in the regression model comparing to the effect estimates of age and group. Comparing with our study with a regular examination every two years over 30 years of follow-up, the Chinese study is advantageous because of much more frequent measurements within a short time period, while the US study compared the changes from the measurement at two time points.

A longitudinal observation of the lung function parameters from 1974 to 1998 based on the present inception cohort was reported in previous publications, with focus on the risk assessment of nitrogen oxides [34,36,37]. From these previous analyses based on the same inception cohort, nitrogen oxides did not show noticeable negative impact on any lung function parameters. Therefore, the impact of nitrogen oxides are not taken into account in the present analysis. The present study with extended follow-up through 2004 is consistent with the former reports [10,11,34,36,37]. The risk estimates of quartz concentration came out to be significantly positive on VC and marginally significant on  $FEV_1$ .

An apparent decline of lung function in 1990 was noticeable in the present cohort. This finding can be the result from: 1) An artefact resulting from the change of measuring devices; 2) A biasing effect due to selection because healthier miners exited from the cohort; 3) True lung function impairment after 15 years of exposure. To check the possible artefact from change of measuring devices, we studied the profile of lung function, grouped according to the measuring devices (refer to Figure 2b). Only 878 lung function tests were performed with bell spirometry from 1974 to 1978. The average FVC for this time period varied between 80% and 85% of predicted value. This finding is not plausible because a primary healthy-worker-effect, i.e. the healthier employees are more likely to be selected into the work force, would be expected from an occupational cohort at the beginning of the exposure [38]. The majority of tests were performed with Vitalograph, whose test results varied from 102% to 109%, which application was abandoned in 1990. Afterwards, Custovit and Body plethysmograph were the major measuring devices since the 90's, which test results were relatively stable over time. The favorable status before the 90's could be a result both from the primary healthy-worker-effect and from the overestimation of Vitalograph readings. The recorded lung function measuring devices showed significant impact on the lung function profile (cf. Figure 2b) in addition to measurement errors. This observation stresses again considering the process of data collection and particularly recording the evolution of measurement devices and techniques during the long-term course of follow up, in order to avoid misinterpretation of data [39,40]. To assure the maximal comparability of the measurements, physicians

and technicians of the occupational health departments were trained for quality management.

A secondary selection occurring during the long-term follow-up [41], either the young or the healthier miners exited from the cohort earlier because of downsizing policy or the unhealthier miners left because of deteriorated health status, might result in a biasing effect. Unfortunately, the reasons for an exit from the cohort were not reliably documented; the biasing effect is, therefore, difficult to be estimated. We checked tentatively in two respects. First, the duration of follow-up approximates the duration of employment (Table 1), we believe that the end of employment, either scheduled retirement or downsizing of workforce, are the major reasons for an exit. Furthermore, we compared tentatively the subgroups of those miners with total exposure duration less than 15 years and the latest exit in 1990 (N = 235) with the remaining cohort (N = 1108) who would have dropped out in 1990 hypothetically. The lung function parameters did not seem to differ systematically. Thus, the censoring status did not seem to be associated with health status.

For exposure assessment, on-going stationary dust measurements were assigned to individual miners. Stationary samplers are considered inferior for measuring a worker's exposure than personal samplers, because the concentration of the respirable dust in the breathing zone of the worker is the relevant parameter for health effect. Dahmann and co-workers discussed the strength and weakness of the personal and static samplers for exposure assessment to silica dust in epidemiological studies [42]. The authors pointed out that the personal samplers usually have considerably lower suction rates than static samplers do, although both suction rates model the human breathing physiology. The influence of the measurement strategies was evaluated by comparing the US (personal) and German (static) samplers by simultaneous sampling. Higher average concentration of the respirable quartz with static sampler was found than that with personal samplers [43].

Information on smoking status and pack-years was based on self-reporting at each medical examination throughout the follow-up period. Both qualitative and quantitative smoking behavior are incorporated into the GEE model in a time-dependent manner, and showed significant impact on lung function profiles. Fletcher and Peto [44] studied the natural history of chronic airflow obstruction in a male cohort, and found that FEV<sub>1</sub> falls gradually over a lifetime. Quitting smoking might contribute to slowing down the deteriorating effect. This finding is supported by the results from the Framingham offspring cohort [45]. Considering the dynamic changes of smoking behavior rather than the information on a given time point represents to be a strength of the study.

Additional strengths of this study are the unique study base of an inception cohort being free of relevant exposure prior to study begin, accompanied with regular dust exposure measurements and repeated medical examinations in approximate 2 years interval for over 30 years. In RAG, a dose-based concept for dust control, based on the cumulative exposure, has been implemented throughout their collieries since 1974. This concept foresees that miners with exposure to

respirable dusts must not exceed a limit value for cumulative exposure to respirable dust evaluated for each miner over an assessment period of 2 years. For more details of this dust control and health surveillance program, please refer to Bauer [13] and Yong, et al. [9]. These findings from the well-established epidemiological coal miner cohorts shed light onto the current issue in terms of exposure to poor soluble low-toxic (PSLT) particulates and non-malignant respiratory diseases.

## Conclusion

Negligible decline of lung function resulted from exposure to coal mine dust, while quartz dust concentration showed adverse effects in the present study. Divergent findings to that of the older studies could be explained partly by different study designs (here: longitudinal studies, no prior exposure), but also by lower dust levels. Stringent dust control measures and health surveillance program might contribute to prevent the respiratory disease.

## Declarations

### Ethics approval and consent to participate

This study is approved from the ethics committee of the University of Cologne, Germany.

### Consent for publication

This manuscript does not contain any individual person's data in any form.

### Availability of data and material

The data of the present study are not accessible publicly.

### Competing interests

The authors declare no competing interests. PM, RD, HL are former employees of RAG. The design, conduct, analysis, and conclusions of the study are exclusively those of the authors.

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### Authors' contributions

Study design and study conduction: PM, HL, RD; Statistical analysis and results interpretation: MY, LA, PM; Drafting and reviewing of the manuscript: MY, LA, HL, RD, PM.

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