ORIGINAL RESEARCH

Pulmonary function and high-resolution computed tomography in outdoor rock drillers exposed to crystalline silica

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ABSTRACT

Objectives Chronic obstructive pulmonary disease and silicosis are associated with exposure to crystalline silica. We determined the exposure to respirable crystalline silica and estimated exposure–response relationships between cumulative exposure and pulmonary function in outdoor rock drillers.

Methods 136 rock drillers and 48 referents were recruited from three heavy construction companies. 98 air samples were collected by personal sampling for determination of respirable particulate matter and crystalline silica. Information about individual job tasks, type of drilling equipment and years of exposure in different job categories was obtained by interview. Cumulative exposure to crystalline silica was calculated for all workers. Pulmonary function was assessed by spirometry. A subgroup of 39 subjects with high cumulative exposure to crystalline silica underwent high-resolution computed tomography (HRCT).

Results Cumulative exposure (mean (min–max)) to crystalline silica was 0.69 mg·years m^{-3} (0.01–5.89) in the exposed group. Mean time of exposure among rock drillers was 10.7 years (1–42). Compared with referents, the rock drillers had a lower forced expiratory volume in one second/forced vital capacity ratio (79.4 vs 81.4, $p<0.05$) and maximal mid-expiratory flow% (85.6 vs 93.9, $p<0.05$). Further, by stratifying the exposed workers into three equally large groups, a dose–response relationship was demonstrated in the highest exposed group, also in never smokers, at a mean cumulative exposure of 21.7 years at 0.08 mg·m^{-3}/years. Silicosis was not detected in HRCT, but other patterns of fibrosis and emphysema were seen.

Conclusions Outdoor rock drillers exposed to crystalline silica had significantly lower pulmonary function than referents, and signs of airflow obstruction. Silicosis was not detected.

Key messages

What is already known about this subject?

- Chronic obstructive pulmonary disease and silicosis are associated with crystalline silica exposure.

What are the new findings?

- In the present study, we found signs of airflow obstruction—without silicosis—in crystalline silica exposed rock drillers. A dose–response association was observed between cumulative exposure to respirable crystalline silica and forced expiratory volume in one second/forced vital capacity ratio and maximal mid-expiratory flow%.
- Importantly, a significant reduction in pulmonary function seems to appear after a mean cumulative exposure to crystalline silica of 0.08 mg·m^{-3} for 21.7 years.
- Never-smokers exposed to crystalline silica showed signs of airflow obstruction, but the degree of airflow obstruction was more severe in ever-smokers.

How might this impact on policy or clinical practice in the foreseeable future?

- This study contributes to regulatory work and highlights the need to reconsider the permissible occupational exposure limit for crystalline silica.

INTRODUCTION

Crystalline silica is a common rock-forming mineral in the earth's crust.[1] In some places, crystalline silica piles up and forms its own crystalline silica-rich deposits.[1 2] Granite, which is a common rock in Norway, may contain up to 24%–40% crystalline silica.[1] Silicosis caused by inhalation of crystalline silica dust particles continues to be an occupational disease of major concern worldwide, and it is well known that exposure to crystalline silica dust particles is a significant contributor to occupational mortality and morbidity.[2 3] Chronic obstructive pulmonary disease (COPD) has also been associated with exposure to crystalline silica, even in non-smokers.[4–11] Longitudinal studies have suggested that signs of airflow obstruction occur with exposure to crystalline silica dust particles at concentrations between 0.1 and 0.2 mg·m^{-3}, but a severe loss of pulmonary function does not occur until after 30–40 years of exposure.[12] A systematic review reported that COPD occurs more often among construction workers than among workers not exposed to construction dust. It was, however, impossible to draw conclusions about specific subgroups since most studies analysed construction

Table 1 Concentrations of particulate matter (PM) in the thoracic and respirable aerosol fractions and respirable crystalline silica according to job categories measured by personal sampling

	Thoracic PM (mg m^{-3})				Respirable PM (mg m^{-3})				Respirable crystalline silica (mg m^{-3})			
Job category	n	AM	GM	Min–max	n	AM	GM	Min–max	n	AM	GM	Min–max
Rock driller using rig with cabin	22	0.17	0.11	0.02–0.69	22	0.09	0.04	<DL–0.36	14	0.01	0.01	<DL– 0.04
Rock driller using radio remote control panel	36	0.81	0.37	0.04–10.4	33	0.26	0.14	<DL– 1.03	15	0.06	0.03	<DL– 0.18
Rock driller using feed mounted control panel	10	4.73	2.96	0.79–22.80	10	1.36	1.07	0.13–2.91	5	0.24	0.22	0.14–0.45
Blasting leader	14	0.20	0.15	<DL–0.54	11	0.09	0.06	<DL–0.28	11	0.02	0.01	<DL–0.06
Rock driller using jackleg drill	10	1.53	1.16	0.39–4.36	9	0.57	0.45	0.16–1.44	9	0.07	0.04	0.01–0.21
Guardrail installer	1	<DL	<DL		13	0.22	0.12	<DL–0.84	13	0.04	0.01	<DL–0.20

AM, arithmetic mean; DL, detection limit; GM, geometric mean; n, number of samples.

workers as one group.[13] The heavy construction industry is an important part of Norwegian industry, employing more than 52 000 workers in 2018.[14] Several job tasks in this industry may generate airborne stone dust containing crystalline silica. The main exposure occurs during rock drilling and blasting.[2 15 16] There is a lack of knowledge regarding exposure levels to dust containing crystalline silica particles generated by different job tasks among outdoor heavy construction workers like rock drillers. To what extent such exposure may cause a decline in pulmonary function is unclear. We therefore aimed to assess exposure to crystalline silica in outdoor rock drillers and determine the effects of such exposure on pulmonary function. We further aimed to find out if exposure had induced silicosis, using high-resolution computed tomography (HRCT) of the chest in a subgroup of workers with high exposure.

MATERIAL AND METHODS

Study design

Three major Norwegian contractors, each with >100 employees and with departments specialising in outdoor rock drilling, were invited to participate in this study. In total, 140 males, working in the immediate vicinity of a drill rig (hereafter called rock drillers), were identified. Since the work sites were spread throughout the country, the medical examinations were carried out at the companies' regional offices during the workers' leisure time, that is, after the end of a 4 days' workweek. Four workers declined to participate. A reference group (n=48), that had never been occupationally exposed to particulate matter (PM) or crystalline silica at work, was recruited among non-exposed heavy construction workers (machine drivers, transport workers) and administrative personnel. Administrative personnel are typically skilled workers who have been promoted to foremen. All males (n=51), who had worked at the offices where the medical examinations were carried out, were invited to participate. Three subjects were away on vacation, the remaining eligible subjects accepted and were included in the study. All participants signed informed written consent declaring their voluntary participation in the study.

Job descriptions

A typical working day lasts 10–12 hours including two 30 min breaks. During drilling operations, the drill rig makes short displacements after each drilled hole. The rock driller operates the drilling rig. In addition to the rock driller, other workers like blasting leaders who are responsible for loading of explosives and guardrail installers, usually work closely to drilling operation. Six different categories were defined, depending on the worker's distance to the drill when carrying out the drilling operation.

1. Rock drillers using drill rigs equipped with feed mounted operation panel. The operator stands close to the drill rod.
2. Rock drillers using drill rigs equipped with radio remote control panel, with the possibility of controlling the drilling from a distance.
3. Rock drillers using drill rigs equipped with radio remote control panel, operated from a closed ventilated cabin.
4. Rock face stabilisers using jackleg drills. The rock drill is mounted on a pneumatic jackleg and is manually controlled by the operator who must stand next to the drilling hole.
5. Blasting leaders having different job tasks close to the drill rigs.
6. Guardrail installers working 10–70 m away from the drill rig.

Clinical examinations

After recording personal data, height and weight were measured and body mass index (BMI) calculated. The study physician interviewed the workers about previous work-related dust exposure, previous and current jobs and type of drilling equipment used. Previous or current medication and health conditions were recorded. Smoking habits were recorded, and pack-years calculated. Subsequently, a health examination, including spirometric measurements, was carried out. A validated, self-administered questionnaire was used to record the presence of lower airways symptoms.[17] It contained questions regarding current occurrence of cough, wheeze, chest tightness, shortness of breath and whether or not the subjects had been diagnosed with asthma by a physician.

Spirometry

Spirometry was performed using the Spirare SPS330 spirometer (Diagnostica, Oslo, Norway). Bronchodilators were not used. The subject was sitting in an upright position with a soft nose clip. All tests were carried out by the same physician, and the accuracy of the spirometer was controlled daily. In order to ensure reproducibility, the measurements were repeated at least three times in accordance with ATS/ERS recommendations.[18] The best time-volume result was used in the statistical analyses. The following measures were recorded: forced vital capacity (FVC), forced expiratory volume in one second (FEV_1), forced expiratory flow at 25% of FVC (FEF_{25}), forced expiratory flow at 50% of FVC (FEF_{50}), forced expiratory flow at 75% of FVC (FEF_{75}) and maximal mid-expiratory flow (MMEF). The pulmonary function variables were expressed in absolute values and as percent of predicted, using (published) reference values for Europeans.[19]

High-resolution computed tomography of the chest

To assess the occurrence of pulmonary silicosis, rock drillers with the highest cumulative exposure to crystalline silica (n=45)

Table 2 Demographics and respirable crystalline silica exposure in 136 crystalline silica exposed rock drillers and 48 referents

	Exposed n=136	Referents n=48
Age, years (AM, min–max)	39.5 (18–72)	37.3 (22–65)
Height, cm (AM, min–max)*	182 (165–198)	179 (166–198)
BMI, kg m^{-2} (AM, min–max)	27.2 (19.8–41.7)	26.2 (21.0–41.4)
Current smokers (%)	19.1	25.0
Former smokers (%)	21.3	14.6
Pack-years in ever smokers (AM, min–max)	14 (0.5–37)	13 (0.8–30)
Self-reported asthma (%)	6.6	10.4
Morning cough (%)*	17.6	2.1
Cough during the day (%)*	27.2	4.2
Wheezing in the chest (%)*	13.2	2.1
FVC L (AM, SD)	5.1 (0.9)	5.3 (0.8)
FVC% (AM, SD)*	99.4 (12.4)	104.7 (10.3)
FEV_1 L/s (AM, SD)	4.0 (0.7)	4.3 (0.6)
FEV_1% (AM, SD)*	96.2 (12.0)	103.1 (10.8)
FEV_1/FVC x 100 (AM, SD)*	79.4 (6.2)	81.4 (4.7)
FEF_{25}% (AM, SD)*	95.8 (20.2)	101.9 (22.9)
FEF_{50}% (AM, SD)*	89.7 (23.6)	98.8 (22.5)
FEF_{75}% (AM, SD)*	71.6 (25.1)	82.3 (26.0)
MMEF% (AM, SD)*	85.6 (22.3)	93.8 (21.9)
Years exposed (AM, min–max)	10.7 (1–42)	n.a
Current exposure to respirable crystalline silica, mg·m^{-3} (AM, min–max)	0.04 (0–0.44)	n.a
Cumulative exposure to respirable crystalline silica, mg·years m^{-3} (AM, min–max)	0.69 (0.01–5.89)	n.a
Cumulative exposure to respirable crystalline silica, $years^{-1}$mg·m^{-3} (AM, min–max)	0.05 (0.004–0.19)	n.a

*P<0.05

AM, arithmetic mean; BMI, body mass index; FEV_1, forced expiratory volume in one second; FVC, forced vital capacity; MMEF, maximal mid-expiratory flow; n.a, not applicable.

were invited to undergo HRCT. Thirty-nine subjects accepted the invitation. Low-dose thin-section CT images of the lungs without intravenous contrast material were performed following a standardised protocol, described elsewhere.[20] The images were reviewed in random order by two experienced chest radiologists blinded to clinical data and pulmonary function tests. The criteria for evaluation of severity of abnormalities have previously been described.[21–23]

Occupational exposure

Air sampling and measurements

Twenty-three construction sites operated by three different companies were chosen for exposure measurements. The sites were chosen because they were considered to be typical for rock drilling activities in Norway. Exposure was measured for all job tasks by personal sampling. The sampling was carried out between 2015 and 2018.

Altogether 98 air samples were collected for the determination of PM of the respirable aerosol fraction. The PM mass was measured in all samples, and respirable crystalline silica in 67 samples. In addition, 93 air samples of the thoracic aerosol fraction were collected, and the PM mass measured. Oil mist and oil vapour were determined in 41 samples. Some personal spot check samples of nitrogen dioxide (NO_2) and carbon monoxide (CO) were also collected, using direct reading instrumentation.

Sampling methods

PM in the respirable aerosol fraction was collected on 5 µm pore size 37 mm polyvinyl chloride (PVC) membrane filters (PVC503500, Millipore Corporation, MA, USA) using respirable cyclones (JS Holdings, Stevenage, UK) operated at 2.2 L min^{-1}. PM in the thoracic aerosol fraction was collected on 5 µm pore size 37 mm PVC membrane filters (PVC503500, Millipore Corporation, MA, USA) using a thoracic cyclone (BGI GK 2.69 sampler, Mesa Labs, CO, USA) operated at 1.6 L min^{-1} flow rate.[24] In-house built PS103 personal sampling pumps were used throughout for the sampling (STAMI, Norway). Calibrated rotameters were used at the beginning and at the end of each sampling period to measure the airflow rates through the samplers. Samples collected with >10% decrease in airflow rate were discarded.

Laboratory analysis

The PM mass was measured by weighing all filters before and after sampling, using a daily calibrated Sartorius MC 5 balance (Sartorius AG, Göttingen, Germany). The accuracy and precision of the measurements were assessed by weighing certified reference masses.[25] The detection limit calculated as 3 SD of all field blanks was 0.04 mg per filter.

The α-quartz content, hereafter termed crystalline silica, was measured by X-ray diffraction spectrometry according to the silver filter method NIOSH Method 7500 (NIOSH, 2003), with a Malvern Panalytical X'Pert³Powder diffractometer, equipped with a PIXcel¹ᴰ detector and an Empyrean X-ray tube (Malvern Panalytical B.V., Eindhoven, the Netherlands). The detection limit was 2 µg.

Calculation of cumulative exposure

A rock driller may have operated several different types of drilling rigs over the years and may also have worked as a blasting leader or with mounting of guardrails. Furthermore, during the last years, drill rigs with feed mounted operation panels have gradually been replaced by rigs with radio remote control panels with or without ventilated cabins. Occupational history was therefore thoroughly assessed by in-depth interview. Based on the collected samples, mean exposure for each of the six job categories was calculated, as shown in table 1. Based on the occupational history and the mean exposure in each of the six job categories, cumulative exposure of respirable crystalline silica was calculated for each exposed worker. This was done by multiplying the number of years spent in each job category with the arithmetic mean (AM) exposure for the given job category. No crystalline silica exposure was known before the workers started as rock drillers. Respiratory protection equipment was generally not used, and therefore no adjustments were made for such use.

Statistics

The distributions of the variables were examined visually. Exposure data were skewed and therefore log-transformed before statistical analysis. Air concentrations of contaminants are presented by AMs, geometric means (GM) and min–max values. Group differences for continuous variables were assessed with independent sample t-test. The relationships between respiratory symptoms (1/0), ever-smoking (1/0) and physician-diagnosed asthma (1/0) were investigated using logistic regression analysis. Univariate associations were evaluated by least-square regression analysis, yielding Pearson's correlation coefficients (Pearson's r) as the measure of association. Multiple linear regression analysis (backwards procedure) was used to assess statistical associations between pulmonary function variables and several independent variables simultaneously. The independent variables were ever-exposed to crystalline silica (1/0), ever-smoker (1/0), age, BMI and physician-diagnosed asthma (1/0). In an alternative approach, pack-years was introduced into the model instead of being an ever-smoker.

Table 3 Results (β-coefficients and p-values) from multiple linear regression analysis (backwards procedure)

	Panel A				Panel B				Panel C			
	Including all 136 crystalline silica exposed rock drillers and 48 referents				Including all 136 crystalline silica exposed rock drillers and 48 referents				Including only 136 crystalline silica exposed rock drillers			
	Ever exposed	Ever smoking	BMI	Asthma	Ever exposed	Pack-years	BMI	Asthma	Cumulative α-quartz exposure	Ever smoking	BMI	Asthma
	β	β	B	β	β	β	β	β	β	β	β	β
FVC%	−4.6*	–	−0.77***	–	−4.6*	–	−0.77***	–	–	–	−0.92***	–
FEV_1%	−6.5**	–	−0.47*	–	−6.5**	–	−0.47*	–	–	–	−0.52*	–
FEV_1/FVCx100	−2.0*	−3.5***	–	–	−1.9*	−0.2***	–	–	−1.9*	−3.0**	–	−4.4*
FEF_{25}%	No model				No model				No model			
FEF_{50}%	−8.9*	−11.7**	–	–	−8.7*	−0.7**	–	–	–	−10.1*	–	–
FEF_{75}%	−10.4*	−15.5***	–	–	−10.2*	−0.8***	–	–	−7.8*	−11.7**	–	−18.8*
MMEF%	−8.0*	−12.0***	–	–	−7.8*	−0.7***	–	–	−6.1*	−9.4*	–	−16.6*

Panels A and B show the results when all participants are included in the analysis, while Panel C presents the results for the exposed subjects only. Independent variables were ever exposed to crystalline silica (1/0), ever being a smoker (1/0), body mass index and self-reported asthma (1/0) (Panel A); for panel B, ever being a smoker was substituted with pack-years and for panel C, ever exposed was substituted with cumulative exposure.
***p<0.001; **p<0.01; *p<0.05; statistically non-significant.
BMI, body mass index; FEV_1, forced expiratory volume in one second; FVC, forced vital capacity; MMEF, maximal mid-expiratory flow.

In those cases, where ever being exposed to crystalline silica was associated with pulmonary function measures, cumulative exposure was added to the model instead of being ever exposed. As a final approach, the exposed subjects were stratified into three equally large groups; low, medium and high cumulative exposure. General linear models were used to calculate mean values of the respective groups adjusted for relevant confounders. A two-tailed p-value<0.05 was considered to be of statistical significance. The statistical data package SPSS V.25.0 was used.

RESULTS

Exposure

Table 1 shows the exposure estimates for each job task that were used for the calculation of cumulative exposure. Table 2 shows

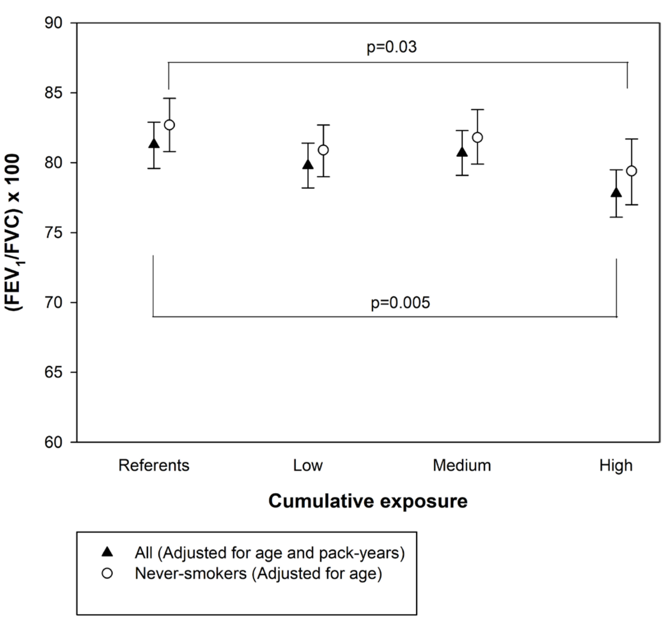

Figure 1 Mean and 95 % CI of (FEV_1/FVC) x100 in referents (n=48) and in rock drillers (n=136) stratified into three groups; low (n=46), medium (n=45), high (n=45) according to cumulative quartz exposure in all participants and in never-smokers. Low: AM 0.059 mg·years m^{-3}, min–max 0.005–0.12. Medium: AM 0.25 mg·years m^{-3}, min–max 0.13–0.38. High: AM 1.76 mg·years m^{-3}, min–max 0.38–5.89. AM, arithmetic mean; FEV_1, forced expiratory volume in one second; FVC, forced vital capacity.

demographics and respirable crystalline silica exposure in 136 crystalline silica exposed rock drillers and 48 referents. The rock drillers had been exposed for 10.7 years on average. There was a strong correlation between air concentrations of respirable crystalline silica and thoracic PM and respirable PM, respectively (Pearson's r=0.86 and 0.87, p<0.0001). Oil mist was detected in two samples only and NO_2 and CO concentrations were negligible.

Clinical findings and respiratory symptoms

The rock drillers and referents were comparable with respect to age, BMI, pack-years in ever smokers and prevalence of physician-diagnosed asthma (table 2). The exposed subjects reported significantly more morning cough, cough during the day and wheezing in the chest. Morning cough was associated with current smoking in both groups. Other non-significant differences in symptoms are not presented. FVC%, FEV_1% and the ratio FEV_1/FVC were significantly lower in the rock drillers than in the referents. Also FEF_{50}%, FEF_{75}% and MMEF% were significantly lower.

Table 3 shows results from the multiple regression analyses with pulmonary function measures as dependent variables and the following independent variables; ever-exposed to crystalline silica (1/0), ever smoking (1/0), BMI and physician-diagnosed asthma (1/0). After taking into account these potential confounders, being ever exposed to crystalline silica was still associated with FVC%, FEV_1%, FEV_1/FVC, FEF_{50}%, FEF_{75}% and MMEF%. Ever being a smoker was also associated with several of these measures, while physician-diagnosed asthma was not. Replacing being an ever-smoker with pack-years in the model gave no significant change in results.

Table 3 also shows the associations between estimated cumulative respirable crystalline silica exposure (lg) and various pulmonary function measures, when only exposed subjects were included in the analyses, adjusting for BMI, asthma and ever smoking. Cumulative exposure was significantly associated with FEV_1/FVC, FEF_{50}%, FEF_{75}% and MMEF%. Being an ever-smoker was also a significant contributor.

Based on the results presented in table 3, the exposed subjects were stratified into three equally large groups according to their cumulative exposure (low, medium and high). FEV_1/FVC was significantly lower in the highest exposed subgroup compared with the referents when adjusted for age and pack-years (p=0.005). Figure 1 shows that all participants had lower FEV_1/FVC in all strata than never-smokers. Highly exposed never-smokers had significantly lower FEV_1/FVC than never-smoking referents adjusted foe age (p=0.03). MMEF% was significantly lower in the highest exposed subgroup compared with the referents when adjusting for pack-years (0=0.008) (figure 2). Highly exposed never-smokers had significantly poorer performance than never-smoking referents (p=0.047). Mean age for the referents was 37.3 years and mean age for the low, medium and high exposed workers were 36.1, 35.7 and 45.9 years, respectively.

The highest exposed group had a mean exposure of $0.08\,mg\cdot m^{-3}$ (min–max $0.024\,mg\cdot m^{-3}$–$0.19\,mg\cdot m$) of respirable crystalline silica for 21.7 years (min–max 3–42 years). No significant effects on pulmonary function were observed in the median exposed group that had a mean exposure of $0.04\,mg\cdot m^{-3}$ of respirable crystalline silica for 7.7 years.

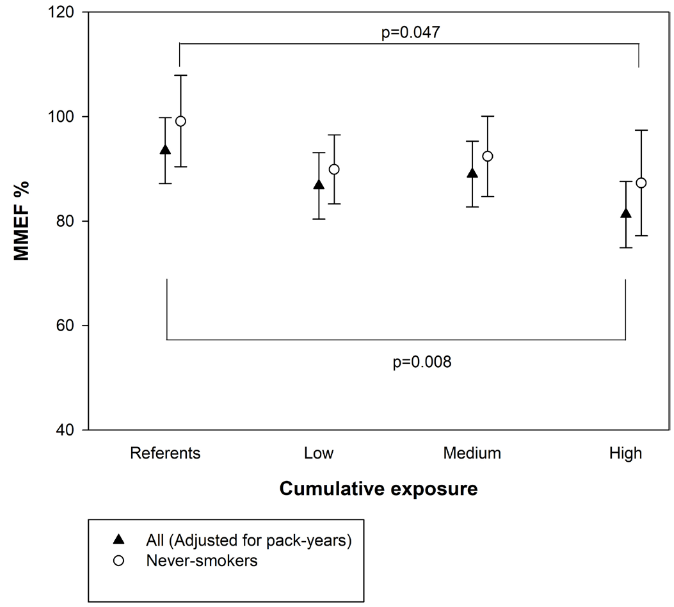

Figure 2 Mean and 95% CI of MMEF% in referents (n=48) and in rock drillers (n=136) stratified into three groups; low (n=46), medium (n=45), high (n=45) according to cumulative quartz exposure in all participants and in never-smokers. Low: AM $0.059\,mg\cdot years\ m^{-3}$, min–max 0.005–0.12. Medium: AM $0.25\,mg\cdot years\ m^{-3}$, min–max 0.13–0.38. High: AM $1.76\,mg\cdot years\ m^{-3}$, min–max 0.38–5.89. MMEF%, maximal mid-expiratory flow%.

HRCT findings

Pulmonary HRCT examinations showed abnormalities in 21 (54%) of the participants in the highest exposed group. Five subjects presented fine intralobular fibrosis with overall extent 5%–10% of the lung volume. One subject presented lung fibrosis with microcystic reticular pattern. Coarse fibrosis with macrocystic pattern and honeycombing was not observed. Emphysema was detected in five subjects. Three of them showed less than 5% overall extent, one 6%–10% and one 10%–20%. All five subjects with emphysema were current or former smokers. Silicosis was not detected in any of the participants undergoing HRCT.

DISCUSSION

This study investigated the effects of exposure to crystalline silica on pulmonary function. Our main finding was that rock drillers with the highest cumulative exposure to crystalline silica had lower FEV_1/FVC ratio and MMEF%, indicative of obstruction in the small airways. This finding was also observed in never-smokers, but the reduction was larger in all participants. Silicosis was not detected in any of the participants undergoing HRCT. Respirable crystalline silica particles are likely to reach the bronchioles and alveoli, leading to silicosis.[2] No signs of honeycombing or other findings suggestive of silicosis were observed on HRCT thorax images among the highest exposed workers. Such findings have not been reported in Norway for decades. However, five workers had microcystic and fine intralobular fibrosis, and an association with exposure to silica cannot be excluded. This could suggest that airways obstruction may be the critical effect of silica exposure, occurring without recognised HRCT signs of silicosis.

There has been some controversy regarding the relationship between exposure to PM from hard rock and the presence of pulmonary disease.[26] However, studies have shown that mineral dust such as crystalline silica may cause airflow obstruction.[5 8 26] In a study of highly exposed South African gold miners, most participants (68%) developed signs of chronic airways obstruction. Only a few (1.4%) showed signs of silicosis.[27 28] It has been reported that chronic exposure to crystalline silica that does not cause disabling silicosis, may cause the development of chronic bronchitis, emphysema and small airways disease.[6 10 12 29 30] Those observations are quite similar to the observations reported in the present study.

Airflow obstruction was observed in those workers who, on average, had been exposed to $0.08\,mg\cdot m^{-3}$ of crystalline silica for 21.7 years. This is shorter duration and lower concentrations than reported in previous longitudinal studies.[12] Those studies have suggested that airways obstruction may occur with exposure to silica dust at concentration levels between 0.1 and $0.2\,mg\cdot m^{-3}$, and that a disabling loss of lung function in the absence of silicosis would not occur until 30–40 years of exposure.[12]

The term 'small airways syndrome' has been used in reference to abnormalities occurring secondary to smoking in the context of COPD.[31] In this study, reduced MMEF%, indicating obstruction in the small airways, was even demonstrated in never-smokers. Fine particles are retained in the lung periphery and the peak deposition occurs in the transition zone and the alveolar region.[32]

COPD is characterised by airflow limitation that is not fully reversible, with or without symptoms. In this study, we did not test reversibility and can therefore not clearly distinguish between COPD and asthma. Of the exposed workers, 8% vs 2% of the referents had FEV_1/FVC ratio <0.7 (not significant, not shown). Only five out of nine exposed workers who reported suffering from asthma used asthma medication, and the diagnosis may be uncertain. Particularly in early-stage airways obstruction, it may be difficult to clinically distinguish between asthma and early-stage COPD. One previous study from Norway found that subjects who enter dusty jobs have better pulmonary function than those who do not (primary health selection), and it is therefore unlikely that asthmatics will apply for jobs where they may be exposed to PM.[33]

The observed relationship between respirable crystalline silica exposure and airflow obstruction may have been biassed. A cross-sectional design generally underestimates exposure effects because sensitive employees may leave the occupation. Misclassification of cumulative exposure might also have occurred because quantitative historical exposure data were not available. Our estimates of cumulative exposure were based on occupational history and exposure measurements carried out before and during the study period, and also on the fact that the drilling technology and type of machinery in use had not changed substantially during the time period when the rock drillers had been employed. The occupational history was based on the assumption that workers remembered the type and duration of previous jobs and what kind of equipment they had used. Therefore, recall bias may have affected the cumulative exposure estimates. Generally, exposure misclassification would tend to decrease observed associations.[34] Most of the air measurements were done during dry weather, without rain or snow. This may have led to overestimation of cumulative exposure, suggesting that the observed effects may occur at even lower exposure levels. However, even though the exact cumulative exposure may have been affected, it is likely that a potential effect of exposure misclassification has been minimised by stratification of the subjects into the three different exposure groups. Temporary differences in crystalline silica exposures may have occurred due to differences in geology across the sites. However, as the construction sites were located across Norway, no systematic long-term differences in crystalline silica exposures were expected. It was assumed that the average exposure levels within the jobs were adequate estimates of the long-term exposure to crystalline silica. The rock drillers were also occupationally exposed to PM other than respirable crystalline silica, which may have contributed to their poorer pulmonary function.

This study was conducted at outdoor rock drilling sites of larger, heavy construction companies in Norway, and the exposure measurements may not be representative for the trade. One could expect exposure to be higher in smaller, often family operated companies, due to less modern equipment, limited resources and a tendency to give priority to production. It should be noted that the reference group also consisted of blue-collar workers, indicating that they belong to the same socioeconomic group as the rock drillers.

CONCLUSION

This study of outdoor rock drillers shows airflow obstruction affecting the small airways in absence of silicosis, occurring at a mean respirable silica exposure of $0.08\,mg\cdot m^{-3}$ for 21.7 years.

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Contributors BU, NPS, MBL and DGE designed the study. MU, TC, BU and NPS were responsible for data collection. AG and TMA reviewed the HRCT. BU and DGE were responsible for statistical analyses and drafting the manuscript. The manuscript was critically reviewed and approved by all authors.

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Patient consent for publication Informed written consent

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