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Original article

EFFECTS OF CUMULATIVE EXPOSURE TO SILICA DUST ON VENTILATORY FUNCTION IN UNDERGROUND MINERS

Latkoska Sanja[1], Minov Jordan[2], Velikj Stefanovska Vesna[3]

[1]PHI Polyclinic Medika, Skopje, Republic of North Macedonia
[2]Institute for Occupational Health of the Republic of North Macedonia, Faculty of Medicine, Ss. Cyril and Methodius University in Skopje, Republic of North Macedonia
[3]Institute of Epidemiology and Biostatistics with Medical Informatics, Faculty of Medicine, Ss. Cyril and Methodius University in Skopje, Republic of North Macedonia
e-mail: sanja.latkoska@gmail.com

Abstract

Introduction: Occupational exposure to crystalline silica is encountered in more workplaces due to its widespread application in multiple industries.

Aim: To assess the impact of estimated cumulative exposure to silica dust on ventilatory function in underground miners.

Methods: A cross-sectional study included 320 underground miners divided in two groups by duration of their work experience (≤ 15 and > 15 years). The study protocol included completion of a questionnaire on demographic and other characteristics, measurements of respirable dust and crystalline silica at the worksite and spirometric measurements.

Results: The mean values of forced vital capacity (FVC) and forced expiratory volume in the first second (FEV1) in underground miners with work tenure ≤ 15 years was significantly higher compared to the mean value in underground miners with longer work tenure (103.35 ± 9.01 *vs.* 97.97 ± 9.94, p=0.00001; and 97.06 ± 11.32 *vs.* 90.84±14.15, p=0.00003; respectively). With increase of work tenure, the values of spirometric parameters significantly decreased, i.e. a significant linear negative correlation between cumulative exposure to silica dust and FVC, FEV1 and FEV1/FVC ratio values was registered (p=0.00003; p=0.00001 and p=0.0104, respectively).

Conclusion: We found a significant impact of cumulative exposure to silica dust on ventilatory function in underground miners. Our findings indicated a need of implementation of more stringent occupational health standards in order to protect respiratory health of exposed workers.

Keywords: crystalline silica, estimated cumulative exposure, forced expiratory volume in the first second, forced vital capacity, work tenure

Introduction

Silicon dioxide or silica is the most abundant mineral on Earth. It is formed from the elements silicon and oxygen under conditions of increased heat and pressure. Silica exists in the crystalline and amorphous forms. Examples of crystalline silica include quartz, cristobalite and tridymite. The most common form of is quartz, a typical component of rocks. Some of the common quartz-containing materials in industry are granite, slate, and sandstone. Granite contains approximately 30% of free silica, slate approximately 40%, and sandstone is almost pure silica. Amorphous silica is non-crystalline and has relatively nontoxic pulmonary properties.

Occupational exposure to silica dust is encountered in more workplaces due to its widespread occurrence in nature, as well as its widespread application in multiple industries. The most important occupations defined by exposure to silica dust are metal and coal mines with underground and above-ground exploitation, construction workers (masons, facade installers, terrace specialists, etc.), production of construction materials, road and tunnel construction; granite processing, slate production and processing, cement and glass production, ceramics and porcelain production, etc.[1-3].

It is well known that long-term exposure to silica dust may cause irritant, toxic and/or carcinogenic effects in the lungs of exposed workers. Long-term exposure to silica dust is associated with occurrence of respiratory symptoms and lung function impairment, i.e. with significant morbidity, disability and mortality. Silicosis, chronic obstructive pulmonary disease (COPD) and lung cancer are considered as the most important lung diseases caused by long-term exposure to silica dust. These diseases may occur independently of each other, in combination of any of them, or all of them in one worker simultaneously. The prevalence of these diseases varies over time and geographical location depending on industries in certain countries and regions, preventive measures taken to protect exposed workers, prevalence of active smoking, etc. On the other hand, the decrease in exposure levels to silica dust in developed countries over the last century has resulted in a dramatic reduction in the morbidity and mortality from silicosis and silicon tuberculosis. Nevertheless, COPD and lung cancer remain an important health problem in workers exposed to silica dust worldwide[4-8].

Lung damage caused by long-term exposure to silica dust, as well as other occupational diseases, is potentially preventable. The primary tool in reducing the morbidity, mortality and disability caused by diseases resulting from long-term exposure to silica dust is the prevention arising from appropriate engineering control, application of protective respiratory equipment, regular periodic medical examinations, and legal regulation of the level of occupational exposure to silica dust. Moreover, the prevention of these diseases will be significantly improved by further research and deepening knowledge of the pathogenetic mechanisms of the chronic effects of silica dust on the lungs of exposed workers[9,10].

Material and methods

Study design and setting

The present study is part of larger research conducted at the Polyclinic Medika, Skopje, in the period June 2024 – June 2025, which investigated respiratory health in underground miners in regard to duration of exposure, i.e. estimated cumulative exposure to silica dust. Ventilatory function was evaluated in a cross-sectional analysis of underground miners with less or more than 15 years of work experience in their current workplace.

Study population

The study population included 320 males, aged 21 to 59 years, working in underground mine for lead and zinc in three work shifts lasting 8 hours. According to the classification of occupational muscular work, underground mining was graded as heavy-to-very heavy work[11]. Study subjects were divided in two groups by their work experience at the actual workplace: a group of workers with work experience less than 15 years and a group of workers with work experience more than 15 years (140 and 180 study subjects, respectively).

Besides other personal protective equipment (helmets, glasses, ear plugs, reflective outfits, gloves, boots, etc.) during their work shifts, all miners used particulate respirator face masks for respiratory protection (3M Aura 9322 + FFP2 Gen 3).

All study subjects were informed about the aim of the study and their written consent was obtained.

Study protocol

The study protocol included completion of a questionnaire on demographic and other characteristics of study subjects, ambiental monitoring, i.e. measurements of concentration of respirable dust (particles with diameter less than 10 μm that can reach alveolar units) and crystalline silica at the worksite, and spirometric measurements.

The questionnaire of demographic and other characteristics of study subjects included items on age, occupational history (working status, total work experience, work experience at the actual workplace, performing of the regular preventive check-ups, etc.), smoking status, and chronic diseases diagnosed by a doctor. Smoking status (active smoker, ex-smoker, non-smoker) was defined by the World Health Organization (WHO) criteria. An active (current) smoker was defined as a subject who smoked at the time of the survey at least once a day, except on days of religious fasting. An ex-smoker (former smoker) was defined as a former current smoker, who no longer smokes. Non-smoker was defined as subject who has never smoked at all, or has never been a daily smoker and has smoked less than 100 cigarettes in his/her lifetime[12].

Measurements of 8-hour exposure to respirable dust and crystalline silica concentration in the respirable dust were done by Laboratory AMBIKON - Campus 2 in "Goce Delchev" University in Shtip, Faculty for Natural and Technical Sciences by standard gravimetric method[13]. Samples were taken using SKC pump with constant flow with cyclone for respirable dust.

Calculation of cumulative (accumulated) exposure to crystalline silica was calculated as follows:

Accumulated crystalline silica dose = fraction of respirable dust* × percentage of free silica in mg/m^3 × number of years of exposure

*Fraction of respirable dust: dust with particles of a size that can reach alveolar units (5 μm: 30%; 1 μm: 100%). Particles larger than 10 μm are deposited in the upper airways by impaction[14].

According to the actual "Rulebook for minimal requests for safety and health at work in workers at risk from chemicals", the limit values for mean 8-hour exposure to respirable dust and crystalline silica in the air at the worksite are 0.45 mg/m^3 and 0.1 mg/m^3, respectively[15].

Spirometric measurements included baseline (pre-bronchodilator) spirometry which was performed in all study subjects and post-bronchodilator spirometry, which was performed in subjects with value of the ratio between forced expiratory volume in 1 second (FEV1) and forced vital capacity (FVC) less than 0.70.

The baseline spirometry, including measures of FVC, FEV_1 and FEV_1/FVC ratio, was performed in all subjects using spirometer Ganshorn SanoScope LF8 (Ganshorn Medizin Electronic GmbH, Germany) with recording the best result of three measurements in which the values of FEV_1 were within 5% of each other. The results of spirometry were expressed as percentages of the predicted values according to the actual recommendations of ERS and ATS. The post-bronchodilator spirometry was performed according to the actual recommendations, i.e. spirometric measurements were performed 20 minutes after administration of 400 μg salbutamol by metered dose inhaler through spacer[16-18].

Statistical analysis

SPSS software package, version 26.0 for Windows, was used for data processing. Qualitative parameters were presented as absolute and relative numbers. Measures of central tendency (mean, median, minimum and maximum values) and measures of dispersion (standard deviation) were used for analysis of spirometric parameters, age, work experience and cumulative exposure. Shapiro-Wilk W test was used to determine the regularity of the frequency distribution of the examined variables. Mann Whitney U test was used to test the significance of the difference between numerical parameters with non-normal distribution. The relationship between length of service as well as cumulative exposure and selected spirometric parameters with irregular frequency distribution was determined by Spearman Rank Order Correlation. Two-sided analysis with a of $p<0.05$ was used for statistical significance.

Results

The study sample consisted of 320 underground miners, with an average age of 40.39 ± 9.31 years and a min/max age range of 21 to 59 years. A total of 25% of subjects were aged ≤33 years and 75% were ≤48 years, with a median IQR=41 (33-48). About 94(29.37%) *vs.* 226 (70.63%) of subjects were with primary and secondary education, respectively. Frequency of active and ex-smokers in the whole study sample was 162(50.62%) and 71(22.19%), respectively.

The mean 8-hour exposure to respirable dust in the air at the workplace was 1.14 ± 0.3 mg/m^3 (range 0.47 to 1.67 mg/m^3) and the mean 8-hour exposure to crystalline silica was 0.019 ± 0.004 mg/m^3 (range 0.007 to 0.024 mg/m^3). The mean estimated cumulative exposure to silica dust was 0.12 ± 0.02 mg/m^3 (range 0.01 to 0.24 mg/m^3).

The average work tenure was 17.54 ± 8.15 years with min/max from 1 to 38 years. A total of 140 (43.37%) subjects had work tenure ≤15 years, with an average cumulative exposure of 0.06 ± 0.03 $Si0_2$ 0.019 mg/m^3. There were 180 (56.43%) respondents with work experience >15 years, whose cumulative exposure was 0.15 ± 0.04 $Si0_2$ 0.019 mg/m^3. In 50% of subjects with work tenure ≤15/ >15 years, the cumulative exposure was ≥0.07 *vs.* ≥0.14 $Si0_2$ 0.019 mg/m^3, respectively.

Table 1. Analysis of spirometric parameters according to work tenure

Parameters	Spirometry parameters						p
	N	Mean±SD	Min/Max	Percentiles 25th	50th (Median)	75th	
Forced vital capacity – FVC (%)							
≤ 15 years	139	103.35±9.01	81/ 124	96	103	110	Z=(-4.874;
>15 years	180	97.97±9.94	68/ 124	91	98	105	p=0.00001*
Total	320	100.32±9.90	68/ 124	94	100	107	
Forced expiratory volume in 1 second - FEV1 (%)							
≤ 15 years	139	97.06±11.32	64/ 121	91	97	106	Z=(-4.119;
>15 years	179	90.84±14.15	62/ 130	82	91	102	p=0.00003*
Total	318	93.56±13.34	62/ 130	86	95	103	
Rate FEV1 / FVC (%)							
≤ 15 years	139	93.60±8.12	64/ 106	91	94	99	Z=(-1.101;
>15 years	179	91.75±13.95	63/ 165	86	93	100	p=0.2708
Total	318	92.56±11.41	63/ 165	89	94	100	
Bronchodilator test - BDT (Post-bronchodilator FEV1) (%)							
≤ 15 years	8	73.62±6.95	67/ 84	67,5	72	79,5	Z=(-1.618;
>15 years	22	66.73±5.97	65/ 95	67	68	68	p=0.1057
Total	30	70.03±6.50	65/ 95	67	68	69	

Mann-Whitney U Test, *significant for p<0.05

The comparison of spirometric parameters in miners with work tenure ≤15/ >15 years indicated a significantly higher mean value of FVC and FEV1 in the group with work experience ≤15 years compared to those with work tenure >15 years (p=0.00001 and. p=0.00003, respectively. Miners with work tenure ≤15 years compared to those with >15 years had for 5.38 ± 0.93% significantly higher FVC and for 6.22 ± 2.83% significantly higher FEV1. In 25% of miners with work tenure ≤15/ >15 years, FVC was >110% / >106% respectively, and FEV1 was >105% / >102%, respectively (Table 1 and Figure 1).

For the FEV1/FVC ratio and for the bronchodilator test BDT (%), i.e. the postbronchodilator FEV1 value in study subjects in whom pre-bronchodilator FEV1/FVC ratio was lower than 0.70, non-significantly higher values were determined in the group with work tenure ≤15 years compared to those with work tenure >15 years, with p=0.2708 *vs*. p=0.1057, respectively (Table 1 and Figure 1).

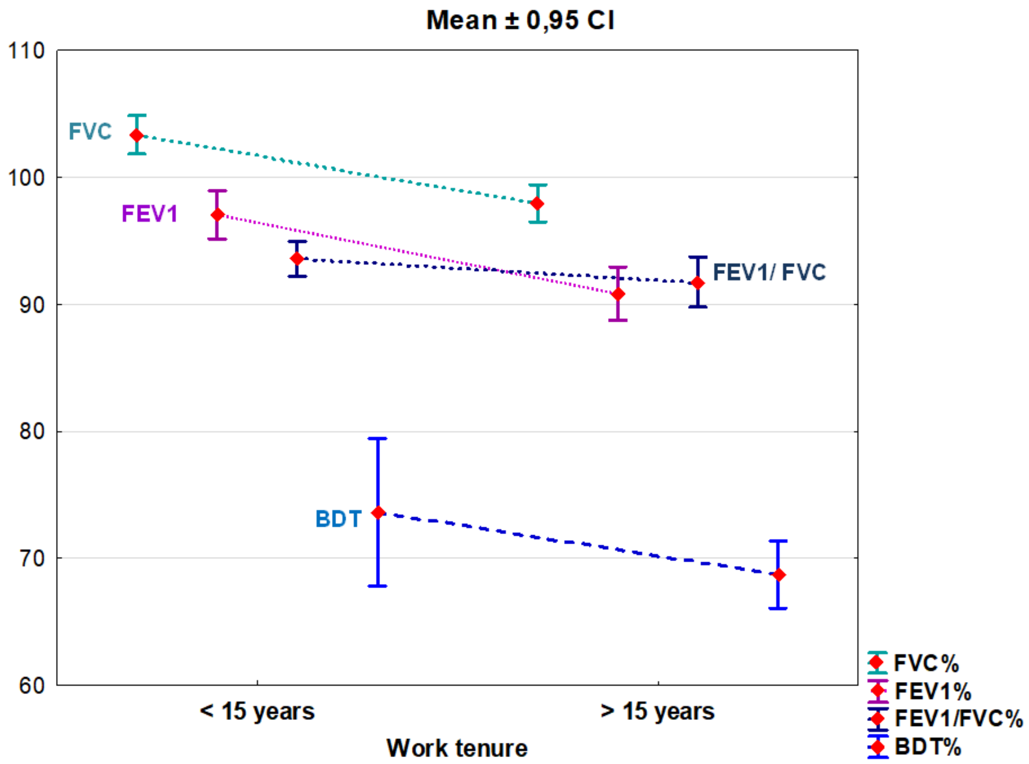

Fig. 1. Average of analyzed spirometric parameters by work tenure

A significant linear negative weak correlation was found between: a) work tenure (years) and FVC (%) for $R_{(318)}$=(-0.252; p=0.00001; b) work tenure (years) and FEV1 (%) for $R_{(318)}$=(-0.257; p=0.00001, and c) work tenure (years) and FEV1/ FVC ratio for $R_{(318)}$=(-0.110; p=0.0485. With increasing work tenure, values of FVC, FEV1 and FEV1/ FVC significantly decreased. A significant linear negative moderate correlation was found between work tenure and BDT for $R_{(318)}$=(-0.437; p=0.0158 – with increasing of work tenure, the obtained BDT values significantly decreased (Table 2 and Figure 2).

The analysis indicated a significant linear negative weak correlation between: a) cumulative exposure and FVC (%) for $R_{(318)}$=(-0.229; p=0.00003; b) cumulative exposure and FEV1 (%) for $R_{(318)}$=(-0.269; p=0.00001, and c) cumulative exposure and FEV1/FVC ratio for $R_{(318)}$=(-0.143; p=0.0104. With increasing of cumulative exposure, values of FVC, FEV1 and FEV1/FVC ratio significantly decreased. A significant linear negative moderate correlation was determined between cumulative exposure and BDT for $R_{(318)}$=(-0.562; p=0.0012 – with increasing of cumulative exposure, the obtained BDT values decreased significantly (Table 2 and Figure 2).

Table 2. Correlation between work tenure and cumulative exposure with analyzed spirometric parameters

Spirometry parameters	Spearman Rang Order correlation - R Work tenure[1]	 Work tenure[1]
Forced vital capacity – FVC (%)	$R_{(319)}$=(-0.252; p=0.00001*	$R_{(319)}$=(-0.229; p=0.00003*
Forced expiratory volume in 1 second - FEV1 (%)	$R_{(319)}$=(-0.257; p=0.00001*	$R_{(319)}$=(-0.269; p=0.00001*
Rate FEV1 / FVC (%)	$R_{(319)}$=(-0.110; p=0.0485	$R_{(319)}$=(-0.143; p=0.0104*
Bronchodilator test - BDT (%)	$R_{(30)}$=(-0.437; p=0.0158*	$R_{(30)}$=(-0.562; p=0.0012*

[1]Work tenure (years), [2]Cumulative exposure (SiO_2 0.019 mg/m^3), *significant for p<0.05

All analyzed spirometric parameters (FVC, FEV, FEV1/FVC and BDT) were significantly negatively correlated with work tenure and cumulative exposure of mining workers (Table 2 and Figure 2).

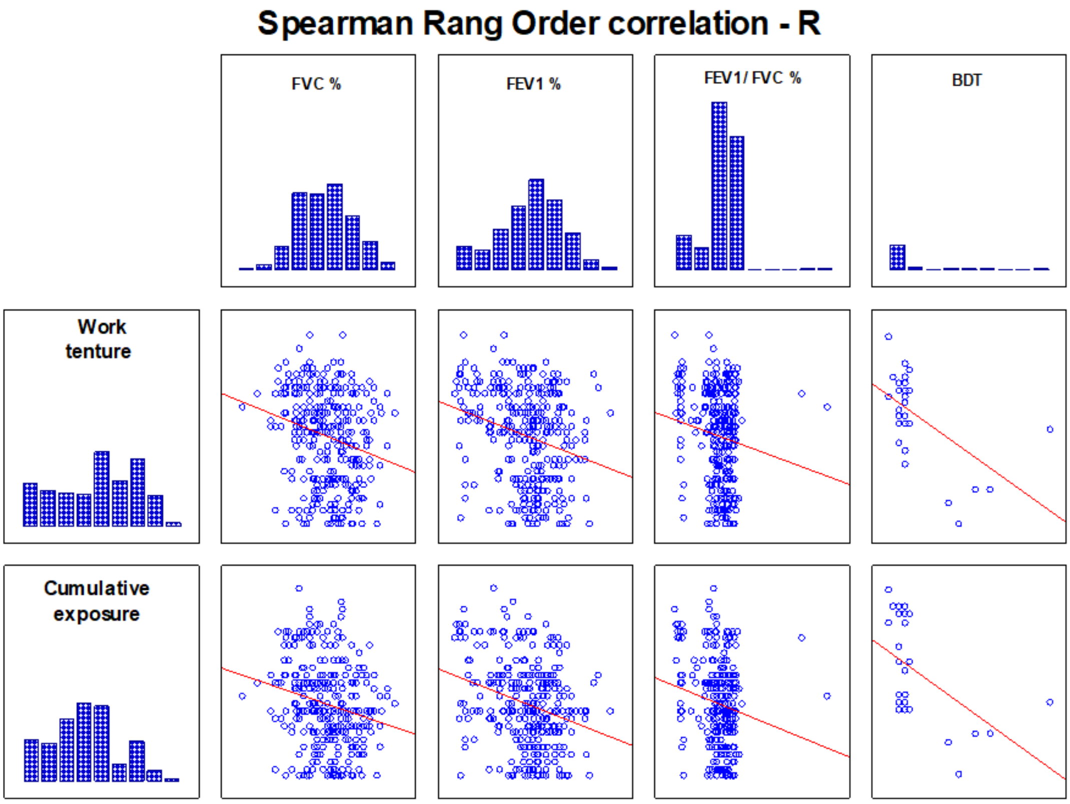

Fig. 2. Correlation between work tenure and cumulative exposure with analyzed spirometric parameters

Discussion

It is well known that long-term exposure to inhalable dust at the workplace, mineral (silica dust, coal dust, etc.) or organic (cotton dust, grain dust, wood dust, etc.), may lead to lung damage and associated respiratory disability[19]. The team of the Institute for Occupational Health of the Republic of North Macedonia, Skopje, have conducted several studies on respiratory effects of mineral and organic dusts in workers from dusty occupations (herbal and fruit tea processors, petroleum refinery workers, bakers, grain workers, etc.) in the last decades in which an excess of respiratory symptoms and lung function impairment were registered[20-23]. The mining industry is particularly prone to dusty environments, so some authors use the concept *Underground Miners Lungs* to describe the lung impairment in underground miners caused by long-term exposure to silica or/and coal dust, diesel particulate matter, elongate mineral particles, toxic gases, etc.[24-26].

In the present study, we assessed the impact of estimated cumulative exposure to silica dust on ventilatory function in underground miners. The study population included 320 males working in underground mine for lead and zinc divided in two groups by their work experience at the actual workplace (equal or less than 15 years and more than 15 years). We found a high proportion of active smokers (a half of the whole study sample) that corresponded to the findings of our previous studies on smoking status of the working population in North Macedonia, indicating poor results of anti-smoking measures and activities[27,28].

The mean 8-hour exposure to respirable dust in the air at the worksite was higher than its actual permissible level, while the mean 8-hour exposure to crystalline silica was 5-fold lower than its actual permissible level. However, several studies have found that current limits do not provide sufficient protection from respiratory impairment, nor is there a limit that can be considered safe and risk-free. Any reduction in exposure will reduce the risk of adverse respiratory effects[29,30]. In addition, the mean estimated cumulative exposure to silica dust in the miners with work tenure equal or less than 15 years was 2.5-fold lower than the mean calculated cumulative exposure to silica dust in miners with work tenure longer than 15 years.

The mean values of FVC and FEV1 in underground miners with work tenure equal or less than 15 years was significantly higher as compared to the mean value in underground miners with longer work tenure. The mean value of FEV1/FVC ratio in miners with work tenure equal or less than 15 years was higher than the mean value with longer work tenure, but statistical significance was not reached. In addition, the mean value of post-bronchodilator FEV1, performed in the study subjects whose pre-bronchodilator value of FEV1/FVC ratio was less than 0.70, was also higher in miners with work tenure equal or less than 15 years but without statistical significance. In our study on respiratory effects of occupational exposure to silica dust in never smoking bricklayers, we found significantly lower values of FVC, FEV1 and FEV1/FVC ratio than their values in unexposed to silica dust (office workers), who served as controls[31].

With increase of work tenure, the values of all analyzed spirometric parameters significantly decreased, i.e. all analyzed spirometric parameters were significantly negatively correlated with the work tenure and with the cumulative exposure to silica dust. The relationship between cumulative exposure to mineral dusts and deficit in lung function were documented in several studies, dominantly in studies including workers exposed to coal dust[32-34]. In a study of 3,380 British coal miners without documented pneumoconiosis, both smoking and coal mine dust exposure were associated with marked reduction in FEV1 (65%)[34]. Longitudinal studies in both British and American coal miners reported similar results, linking estimated dust exposures with rates of FEV1 decline[35,36]. Among a group of 904 young lignite miners exposed to relatively low dust levels in a Sardinian mine, individual exposures to coal mine dust were related to rates of longitudinal decline in FVC and FEV1 during follow-up after accounting for age, smoking and initial FVC and FEV1 values[37].

The findings of the present study must be interpreted within the context of its limitations. Firstly, a cross-sectional analysis used in the study could not provide a causal relationship between silica dust exposure and ventilatory function changes in exposed miners. Secondly, the association between spirometric parameters and other factors that could have an impact on ventilatory function, such as smoking, age, diesel exhaust in the underground mining environment, etc., were not analyzed. This may have certain implications on the data obtained and their interpretation. In addition, the impact of healthy worker effect (HWE) that is considered as the most common selection bias in occupational studies can not be excluded. On the other hand, the findings of the present study contribute to the knowledge about the effects of cumulative exposure to silica dust on lung function in workers in underground metal mines, a field with limited number of studies.

Conclusion

In conclusion, in this cross-sectional study on the impact of relatively low cumulative exposure to silica dust on ventilatory function in underground miners, we found significantly higher mean values of FVC and FEV1 in miners with work tenure equal or less than 15 years than their mean values in miners with work longer than 15 years. In addition, there was a significant linear negative correlation between FVC, FEV1 and FEV1/FVC ratio and cumulative exposure to silica dust. Our findings indicated a need of improvement of preventive measures and activities, i.e. appropriate engineering control, application of protective respiratory equipment, regular periodic medical examinations, and legal regulation of the level of silica dust exposure in order to reduce the lung damage in underground miners.

Competing Interests

All authors hereby have declared that no competing interests exist.

Authors Participation

SL participated in data collection, data analysis, and writing all versions of the manuscript, MJ and VSV participated in data analysis and writing all versions of the manuscript. All authors read and approved the final version of the manuscript.

Conflict of interest statement. None declared.

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