REVIEW

LUNG EFFECTS OF LONG-TERM OCCUPATIONAL EXPOSURE TO SILICA DUST

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Abstract

Silicon dioxide, also known as silica, is one of the most abundant minerals in the Earth's crust, occurring in both crystalline and amorphous forms. The most common form of crystalline silicon dioxide is quartz; while the most common materials in the industry which contain quartz are sand, gravel, and rock. Occupations with the highest risk of exposure to dust containing free silicon dioxide are: metal and coal mining with underground and above-ground exploitation; construction-related activities (workers such as builders, facade installers and terrace specialists, etc.), production of building materials, road and tunnel construction, granite processing, production and processing of slate, production of cement and glass, production of ceramics and porcelain, etc. The inhalation of crystalline silicon dioxide is considered a health risk. Long-term occupational exposure to dust containing free silicon dioxide may cause irritant, toxic and/or carcinogenic effects to the lungs in exposed workers. The principal occupational diseases caused by inhalation of free silicon dioxide are silicosis, chronic obstructive pulmonary disease (COPD) and lung cancer, as well as a combination of these diseases. The primary tool in reducing morbidity, mortality and disability caused by diseases associated with exposure to free silicon dioxide is the prevention based on appropriate engineering controls, protective respiratory equipment, regular periodic medical examinations and legal regulation on the level of occupational exposure to free silicon dioxide.

ПРЕГЛЕД НА ЛИТЕРАТУРА

ЕФЕКТИ ВРЗ БЕЛИТЕ ДРОБОВИ НА ДОЛГОТРАЈНАТА ПРОФЕСИОНАЛНА ИЗЛОЖЕНОСТ НА ПРАШИНА ШТО СОДРЖИ СЛОБОДЕН СИЛИЦИУМ ДИОКСИД

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Печатарски права: ©2025 Сања Латкоска, Јордан Минов. Оваа статија е со отворен пристап дистрибуирана под условите на нелокализирана лиценца, која овозможува неограничена употреба, дистрибуција и репродукција на било кој медиум, доколку се цитираа ториганалниот(ите) автор(и) и изворот.

Конкурентски интереси: Авторите изјавуваат дека немаат конкурентски интереси.

Извадок

Силициум диоксидот е еден од најзастапените минерали во Земјината кора, а се јавува во кристална и аморфна форма. Најчест вид на кристалниот силициум диоксид е кварцот, а најчесто користени материјали што содржат кварц се песокот, чакалот и каменот. Работни места кои се со највисок ризик на изложеност на слободен силициум диоксид се: рудниците на метали и јаглен со подземен и надземен коп, градежништвото (ѕидари, фасадери, терацери и др.) и производството на градежни материјали, изградбата на патишта и тунели, производството на цемент и стакло, производтвото на керамика и порцелан и др. Инхалацијата на прашина што содржи слободен силициум диоксид е докажан ризик за здравјето на изложените работници. Долготрајната професионална изложеност на слободен силициум диоксид може да предизвика иритативни, токсични и/или канцерогени ефекти врз белите дробови на изложените работници, а најчести професионални болести предизвикани од долготрајната изложеност на слободен силициум диоксид се: силикозата, хроничната опструктивна белодробна болест и канцерот на белите дробови, како и која било нивна комбинација. Примарна мерка во намалувањето на морбидитетот, морталитетот и онеспособенсота од болестите поврзани со професионална изложеност на прашина што содржи слободен силициум диоксид е превенцијата базирана врз мерките за инженерска контрола, примената на лични заштитни средства, редовно изведување на периодичните здравствени прегледи и одржување на концентрациите на слободен силициум диоксид на работното место во рамки на дозволените граници.

Introduction

Following oxygen, silicon (Silicium - Si) is the most abundant mineral in the Earth's crust, accounting for an estimated 27% of its composition. On the other hand, silicon dioxide, is its most common compound, occurring as free silicon dioxide, also known as silica, and bound silicon dioxide in multiple compounds, so-called silicates. In occupational pathology, occupational exposure to silica dust is of particular concern due to its harmful effects on the health of exposed workers.

Silica is encountered in crystalline and non-crystalline (amorphous) form; while the heated non-crystalline silica becomes crystalline silica. The most important natural minerals that contain crystalline silica are quartz, cristobalite, and tridymite, with quartz being the most prevalent. The principal industrial materials containing quartz are sand, gravel, and granite. Granite contains approximately 30% of pure silica, grave approximately 40%, while the sand represents almost pure crystalline silica.

Synthetic forms of crystalline silica include keatite, silica W, porosyl, etc. Dust released from naturally occurring forms of amorphous silica (diatomite, glass silicon dioxide, silicon dioxide fibers, etc.) and forms of synthetic amorphous silicon dioxide (colloidal silica, silica, etc.) has milder effects on the lungs[1, 2].

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. It is estimated that in the United States, between 1.2 and 3 million workers were exposed to dust containing free silicon dioxide in the first decade of this century.

Occupations with the highest risk of exposure to silica dust include metal and coal mining with underground and above-ground exploitation, as well as construction-related activities (workers such as 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]

Confirmed by the results of clinical-epidemiological and experimental studies, the effects of silica dust on the respiratory health of exposed workers have been known for a long time. Their prevalence 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 morbidity and mortality from silicosis and silicon tuberculosis. Nevertheless, COPD and lung cancer remain a health problem in workers exposed to silica dust.

The concentration of silica in the dust inhaled while working, as well as the characteristics of the inhaled dust and the duration of exposure, are closely related to the frequency and degree of severity of the lung damage. At the same time, individual (endogenous) characteristics of exposed workers play a major role in the lung

damage, including congenital and acquired abnormalities of mucociliary clearance in the respiratory tract, along with previous respiratory infections.

The effects of silica on the lungs can be acute, subacute, and chronic. Depending on the mechanism of lung tissue damage, they can be irritating, toxic, and carcinogenic. The most important acute and subacute effects on the lungs of exposed workers are acute or subacute silicosis. Long-term occupational exposure to free silicon dioxide in exposed workers can lead to silicosis, chronic obstructive pulmonary disease (COPD) and lung cancer, a combination of any of these diseases, or all three diseases in one worker simultaneously. Chronic lung diseases caused by occupational exposure to dust containing free silicon dioxide are among the most important diseases in occupational lung pathology. At the same time, these diseases are of particular public health importance in terms of their frequency and the large number of workers exposed to dust containing free silicon dioxide throughout their working engagement[3, 4].

The aim of the paper is to present current knowledge about harmful lung effects of silica dust, pathogenesis of chronic lung diseases caused by occupational exposure to silica dust, their diagnosis and treatment, as well as about measures and activities for their prevention.

Silicosis

Silicosis is a fibrogenic pneumoconiosis caused by inhalation of silica dust, its deposition in the lungs, and lung tissue reaction to the inhaled dust. The disease has been included in the List of Occupational Diseases of the Republic of North Macedonia since 2020, designated as *301.11. Silica* and *301.12. Silicosis combined with pulmonary tuberculosis*[5]. On the 2010 List of Occupational Diseases of the International Labour Organization (ILO), Silicosis is designated as *2.1.1. Pneumoconioses caused by fibrogenic mineral dust (silicosis, anthraco-silicosis, asbestosis)* and *2.1.2. Silicotuberculosis*[6].

In the second half of the 19th and first half of the 20th centuries, silicosis was considered as the most common occupational lung disease worldwide, resulting in a high rate of disability and mortality especially among coal and metal miners. With the implementation of adequate preventive measures and activities (legal regulation of the level of exposure to silica dust, application of personal protective equipment, regular periodic examinations of exposed workers, etc.), the prevalence of silicosis, as well as its degree of severity, has been significantly reduced, but this disease still has a significant place in occupational lung pathology[7, 8].

A silicosis nodule is a major pathohistological change in silicosis. Inhaled particles of silica penetrate deep into the alveolar ducts and sacs and are difficult to eliminate through mucus by coughing. The silicosis genesis is considered a key element in the interaction between deposited particles and alveolar macrophages. Alveolar macrophages ingest the deposited particles, thus inducing an inflammatory response by releasing cytokines (tumor necrotizing factor-α, interleukin-1, leukotriene-B4, etc). Cytokines stimulate fibroblasts to proliferate

and produce collagen around the silica dioxide particles, resulting in fibrosis and the formation of nodular lesions in the lungs[9, 10].

Silicosis may take acute, accelerated or chronic forms. The acute form occurs with exposure to very high concentrations of silica dust over a period of several months, while the accelerated form with exposure to high concentrations of free silicon dioxide over a period of several years. As a result of the implementation of the above-mentioned preventative measures, these two forms have not been reported in developed countries, including ours, for the last couple of decades.

The chronic form of silicosis is its most common form occurring with occupational exposure to moderately high and low concentrations of silica dust in a period of at least two decades. It may occur as classical or simple silicosis, or as progressive massive fibrosis (PMF), i.e. a severe form of chronic silicosis characterized by confluence of the silicosis changes and expressive pulmonary fibrosis. The simple chronic silicosis is oftentimes asymptomatic and is detected with radiologic imaging at periodic health examinations; whereas the chronic PMF silicosis is characterized by severe damaging of the lung morphology and function, which progresses to chronic respiratory insufficiency (CRI).

Silicosis is often accompanied by other diseases that significantly aggravate its course and prognosis, including anthracosis (silico-anthracosis), COPD and bronchiectasis, tuberculosis (silico-tuberculosis), lung cancer (silico-carcinoma), systemic diseases of the connective tissue, such as rheumatoid arthritis (Caplan syndrome), systemic lupus, progressive systemic sclerosis, dermatomyositis, and others[11, 12].

The diagnosis of silicosis is based on the data from the medical and work history, the radiological findings interpreted in line with the current recommendations of the ILO, the results of the functional lung tests, etc. The treatment of the disease is symptomatic, and the further work on the patient depends on the results from the working capacity assessment, i.e. on the severity of the functional damaging of the lungs and the degree of occupational exposure to silica dust. Prevention, including adequate engineering measures to control exposure, application of personal protective equipment and regular implementation of preventive medical examinations of exposed workers, are of key importance in the management of silicosis[13-15].

Chronic obstructive pulmonary disease (COPD)

Results arising from numerous studies indicate that long-term occupational exposure to silica dust can contribute to the development of chronic bronchitis, emphysema and/or diseases of the small respiratory tract in the absence of radiologically confirmed silicosis, i.e. that the occurrence of COPD can cause silica concentrations that do not lead to the occurrence of silicosis. In recent years, the academic literature uses the term COPD caused by silica dust (silica-induced COPD). Additionally, cigarette smoke emphasizes the effect of silica on the respiratory tract (the combined effect of silica and tobacco smoke is not additive, but mul-

tiplicative), as well as disability and mortality from COPD[16-18].

According to the results of existing animal model studies, the mechanism of COPD in workers exposed to silica dust does not differ from the mechanism of COPD in smokers (tobacco smoke-induced COPD): however, it is due to the disruption of the balance of proteinases and antiproteinases in the lung tissue in favor of proteinases.

Pulmonary changes are mostly emphasized in the peripheral airways (small bronchi and bronchioles), the pulmonary parenchyma (respiratory bronchioles, alveolar ducts and sacs), and in the pulmonary blood vessels. The changes are initiated by toxic and inflammatory processes in the respiratory tract and pulmonary parenchyma triggered by the release of mediators that stimulate the production of cytokines, chemokines, elastase and fibrogenic factors.

Dominant inflammatory cells involved in the thickening of the airway wall and destruction of the pulmonary parenchyma are neutrophils, macrophages, and T lymphocytes (CD8+ and CD4+). The thickening of the small airways and the narrowing of their lumen and centrilobular emphysema (identical to the type of emphysema that occurs in tobacco-induced COPD), lead to a persistent and progressive decrease in airflow through the airway. Over time, these changes can lead to a disruption of respiratory gas exchange (RGE) in the lungs, an increase in pulmonary arterial pressure (pulmonary arterial hypertension - PAH) and the development of chronic pulmonary heart.

The appearance of COPD in workers exposed to free silicon dioxide depends on the level and duration of the exposure, as well as on their individual characteristics (genetic factors, exposure to tobacco smoke, previous respiratory infections, etc.). In terms of the level of exposure, research results indicate that cumulative exposure to free silicon dioxide at average concentrations of 0.1 to 0.2 mg/m^3 can lead to the occurrence of COPD without the occurrence of accompanying silicosis, i.e. an unsafe limit with respect to the occurrence of COPD is considered occupational exposure to free silicon dioxide at concentrations higher than 0.1 mg/m^3. In terms of the duration of exposure, no specific threshold has been defined, but according to several experts in the field, COPD in workers exposed to silica dust is associated with cumulative exposure at the specified concentrations over a period exceeding 15 years [19-22].

The diagnosis of occupational COPD caused by inhalation of silica dust, as with the diagnosis of other occupational diseases, is based on evidence of a causal relationship between the disease and the workplace in a worker diagnosed with COPD. Evidence of a causal consequential relationship between the disease and the workplace is based on data from the work history (period and degree of occupational silica exposure) and on data from the risk assessment of the patient's workplace (results of measurements carried out during environmental monitoring).

Concerning the recognition of the occupational character of COPD, there is a discrepancy between the ILO List of Occupational Diseases and the List of Occupational Diseases of the Republic of North Macedo-

nia. The latter has to be corrected with the upcoming updates in our national list consistent with existing knowledge on the role of occupational agents in the development of the disease. COPD caused by occupational exposure to silica dust is included in the ILO List of Occupational Diseases alongside forms of COPD caused by other occupational agents for which etiopathogenetic mechanisms in the contingency of the disease have been confirmed *(2.1.9. Chronic obstructive pulmonary disease caused by inhalation of coal dust, dust from stone quarries, wood dust, dust from cereals and agricultural work, dust in animal stables, dust from textiles, and paper dust, arising from work activities)*, whereas the occupational nature of the disease is not linked to the smoking status of the sick worker[6]. COPD caused by occupational agents is reported only in workers in underground coal mines in the List of Occupational Diseases of the Republic of North Macedonia *(307. Chronic obstructive bronchitis or emphysema in miners working in underground coal mines)*, in which recognizing the occupational character of the disease requires that the affected worker must have never smoked in his life[5].

Treatment of COPD caused by occupational exposure to silica dust includes applying pharmacological therapy, as well as the implementation of non-pharmacological measures and activities according to the recommendations of the current guidelines. In terms of further management of the patient, the treatment depends on the results of the assessment of the working capacity, i.e. on the degree of severity of the functional impairment of the lungs and the degree of occupational exposure to silica dust. As in the case of silicosis prevention, adequate engineering measures to control exposure, the application of personal protective equipment and the regular implementation of preventive medical examinations of exposed workers are of key importance in the management of silica-induced COPD.

Lung cancer

Lung cancer is the most common malignant neoplasm in men and one of the most common malignant neoplasms in women in recent decades. The therapeutic possibilities are still limited, making the five-year survival only found in a small percentage of the diagnosed patients. Risk factors for lung cancer include exposure to tobacco smoke, radon, asbestos, polycyclic hydrocarbons, etc.

As reported by the International Agency for Research of Cancer (IARC), silica (quartz) is a proven human carcinogen for lung cancer according to the results of clinical epidemiological and experimental animal model studies, while the carcinogenic effects of natural and synthetic amorphous silicon dioxide show inconclusive evidence[23, 24, 25].

Lung cancer in workers exposed to silica dust (silicon carcinoma) can occur in workers with silicosis and/or COPD but can also occur in previously intact lungs. In its histological characteristics, clinical manifestations and therapeutic possibilities, silicon carcinoma does not differ from lung cancer of other etiologies.

The diagnosis of lung cancer caused by exposure to silica dust, i.e. the evidence of the causal relationship of the disease with the workplace, de-

rives from work history data (period and degree of occupational silica exposure) as well as from the data from the risk assessment of the patient's workplace (results of the measurements carried out during the environmental monitoring).

Once again, as in the case of other diseases resulting from chronic effects on the lungs of occupational exposure to silica dust, measures of primary prevention (control of occupational exposure) and secondary prevention (early detection of the disease by regularly conducting periodic preventive examinations in exposed workers and early intervention) are crucial in the management of silicon carcinoma[26, 27, 28].

Lung cancer caused by occupational exposure to silica dust is not yet included in the National List of Occupational Diseases, while in the ILO List of Occupational Diseases, is included under *3.1.21. Cancers caused by other agents at work not mentioned in the preceding items where a direct link is established scientifically, or determined by methods appropriate to national conditions and practice, between the exposure to these agents arising from work activities and the cancer(s) contracted by the worker*[5, 6].

Conclusion

Long-term occupational exposure to silica dust may cause irritant, toxic and/or carcinogenic effects to the lungs in exposed workers. Diseases caused by occupational exposure to silica dust, as well as other occupational diseases, are potentially preventable.

The primary tool in reducing 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 occupationally exposed workers.

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