ORIGINAL ARTICLE

Risk Assessment of Mortality from Silicosis and Lung Cancer in Sweepers of an Iron Ore Mine with Crystalline Silica Exposure

Haniyeh Soltanpour[1], MSc; Ali Faghihi Zarandi[1], PhD; Abdollah Gholami[2], PhD; Saiedeh Haji-Maghsoudi[3], PhD; Behnam Khodarahmi[4], MSc; Rouhollah Parvari[1], PhD

[1]Department of Occupational Health Engineering and Safety at Work, Faculty of Public Health, Kerman University of Medical Sciences, Kerman, Iran
[2]Department of Occupational Health, School of Health, Social Department of Health Research Center, Birjand University of Medical Sciences, Birjand, Iran
[3]Modeling in Health Research Center, Institute for Futures Studies in Health, Kerman University of Medical Sciences, Kerman, Iran
[4]Department of Occupational Health Engineering, Gol-E-Gohar Mining and Industrial Co, Sirjan, Iran

Correspondence:
Rouhollah Parvari, PhD;
Department of Occupational Health Engineering and Safety at Work, Faculty of Public Health, Kerman University of Medical Sciences, Postal code 76169-13555, Kerman, Iran
Tel: +98 34 31325458
Email: parvari64@gmail.com
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Abstract

Background: Crystalline silica is a major occupational air pollutant. Inhalation of silica-containing dust can lead to severe respiratory disorders, including silicosis and lung cancer. This study assessed the mortality risks of silicosis and lung cancer among sweepers at an iron ore mine exposed to crystalline silica.
Methods: A cross-sectional study was conducted during 2022–2023 involving 120 sweepers and 120 office staff. Air sampling for crystalline silica was performed using plastic cyclones in accordance with NIOSH Analytical Method 7601, and samples were analyzed using a UV/VIS spectrophotometer. Mortality risk assessments for silicosis and lung cancer were computed using the Mannetje and Rice models, respectively.
Results: The mean concentration of crystalline silica exposure among sweepers (0.67±1.40 mg/m³) exceeded the permissible exposure limit (PEL) of 0.025 mg/m³. The Concentration unit showed the highest silica levels. The estimated silicosis mortality risk ranged from 3–64 per 1,000 workers among sweepers and 1 per 1,000 workers among office staff. The lung cancer mortality risk ranged from 9–535 per 1,000 sweepers and 1 per 1,000 office staff. The Concentration unit also exhibited the highest risk for both diseases.
Conclusion: Sweepers in iron ore mines face elevated mortality risks from silicosis and lung cancer due to excessive crystalline silica exposure. Effective control measures to reduce silica levels are urgently needed. Further investigations should address long-term exposure patterns and preventive strategies.

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Introduction

Poor air quality in the workplace, stemming from the release of airborne pollutants, can lead to significant health problems.[1] Among these pollutants are dusts—solid particles generated by mechanical processes. In industries such as mining, silica is a prevalent dust, often resulting from mineral grinding, blasting, and crushing operations.[2] Silica, composed of silicon and oxygen atoms, has a melting point of approximately 1600°C.[3] It is typically colorless and odorless. It exists in both crystalline and amorphous forms, with crystalline varieties such as cristobalite, tridymite, and quartz being particularly toxic and harmful, thereby classifying them as significant air pollutants.[4]

Crystalline silica poses a greater health risk than its amorphous counterpart and is commonly encountered in various industries, including construction, mining, foundries, cement manufacturing, and sandblasting.[5] While historically inert dusts with less than 1% quartz were considered less hazardous, recent research indicates that even these dusts can cause chronic lung diseases with prolonged exposure to high concentrations.[6] Consequently, numerous workers across the United States, Europe, and China are exposed to crystalline silica dust in recent studies.[7] The International Agency for Research on Cancer (IARC) classifies crystalline silica as a Group 1 carcinogen, with the current threshold limit value (TLV) set at 0.025 mg/m^3.[8] Echoing these concerns, a study conducted in an iron ore mine by Naghizadeh et al. reported silica concentrations ranging from 0.01 to 1.5 mg/m^3, with a majority exceeding the occupational exposure limit.

Exposure to crystalline silica dust is a recognized occupational hazard, strongly linked to severe respiratory diseases, including silicosis and lung cancer.[5] Lung cancer, in particular, is a significant consequence, with the risk amplified by occupational exposure.[7] The pathological process is initiated upon inhalation of silica particles, which can reach the deep respiratory zones. This triggers an inflammatory cascade that damages the pulmonary system, ultimately increasing the risk of developing cancer.[9] Numerous epidemiological studies have consistently demonstrated a correlation between crystalline silica exposure and the development of chronic respiratory diseases.[8] For instance, lung cancer, a leading cause of cancer-related mortality in France in 2015, was attributed to occupational exposure in 5–15% of cases.[10] Early diagnosis of lung cancer, particularly before the onset of lethal metastasis, is crucial for reducing mortality rates.[4] Reflecting the severity of this risk, a study by Mohammadi et al.,[11] in an industry with high silica exposure, a lung cancer mortality risk ranging from 7 to 94 per thousand individuals was reported—a notably high incidence.

Beyond cancer, silicosis is another debilitating disease resulting from silica contact, characterized by progressive scarring of the lungs. Silicosis manifests in several forms: acute, accelerated, and chronic. Acute silicosis typically develops within five years of exposure. The accelerated form arises more rapidly after exposure to high concentrations, while chronic silicosis emerges after 10 or more years of exposure to lower levels.[5] Silica concentration and duration of exposure are the most significant risk factors for the development of this disease.[9] Pulmonary fibrosis is a common and severe outcome of silicosis. The United States has reported thousands of new silicosis cases annually over the past nine years, underscoring the critical need for prevention and control measures.[8] While studies have established a clear link between silica exposure, silicosis, and mortality, death from this disease is most likely when exposure conditions remain uncontrolled.[12] Recognizing the global burden of silicosis, the World Health Organization (WHO) and the International Labor Organization (ILO) have set a joint goal to eradicate the disease by 2030.[6]

Previous investigations into the health risks associated with occupational pollutant exposure consistently highlight the necessity for rigorous monitoring and preventive strategies.[13] Risk assessment models serve as practical and effective tools for these purposes, particularly within the mining and industrial sectors. Regarding crystalline silica exposure, two primary models have been established to quantify mortality risk: the Rice model, which measures the excess lifetime mortality risk attributed to lung cancer,[11] and the Mannetje model, used to assess the mortality risk associated with silicosis.[3]

The Occupational Safety and Health Administration (OSHA) has established one death per 1,000 individuals as the acceptable threshold for mortality risk.[9] In the United States, current screening guidelines emphasize the importance of monitoring and recommending annual evaluations for high-risk populations.[8, 12, 14, 15]

Mines represent a high-risk environment, with studies indicating that the incidence of disease and injury in mining operations can be up to six times higher than in other industries.[16] In such settings, the role of a sweeper, particularly in an iron ore mine in southeastern Iran, poses a distinct occupational hazard. These individuals are primarily responsible for the manual cleaning of floors and surfaces, a task that involves direct and often intense exposure to accumulated dust. Consequently, sweepers in these roles can experience dust exposure levels twice as high as those in other occupational groups within the mine.

Critically, previous research has often aggregated sweepers with broader “exposed groups,” failing to acknowledge the unique work processes and exposure conditions that differentiate them. While studies on urban sweepers are more common, a significant gap remains in understanding the specific health implications and disease risks faced by their industrial counterparts.[4, 17-20] Given the escalating concerns regarding the adverse health effects of silica exposure documented in prior research, this study is specifically designed to address this gap. We aim to meticulously assess the mortality risks of silicosis and lung cancer among sweepers employed at an iron ore mine with known exposure to crystalline silica.

Methods

Participants

This cross-sectional study was conducted at an iron ore mine in southeastern Iran. The objective was to quantify crystalline silica concentrations and evaluate the associated mortality risks among mine sweepers. The study population was divided into two cohorts: the exposed group, consisting of 120 sweepers who spent the majority of their shifts in areas with high dust concentrations, selected via a census approach; and a control group, comprising 120 office staff, randomly selected from the same facility, where dust concentrations were documented as minimal.

Exposure Assessment

Airborne crystalline silica sampling and analysis were conducted from October 2022 to March 2023, in accordance with the National Institute for Occupational Safety and Health (NIOSH) Method 7601. Samples were collected using plastic cyclones equipped with polyvinyl chloride (PVC) filters, with the cyclones maintained at a flow rate of 3 L/min. Sampling duration was determined based on preliminary field tests.

For sample preparation, a reagent suite including nitric acid, perchloric acid, phosphoric acid, hydrofluoric acid, boric acid, sulfuric acid, and molybdate reagent was utilized. Sample analysis was performed using a UV/VIS spectrophotometer at a wavelength of 420 nm or 820 nm. Crystalline silica concentrations in the sampled air were calculated using the following equation.[21]

$$C = \frac{W_m - W_b}{F \times T} \tag{1}$$

Where W_m and W_b are the weights of silica in the main and blank samples, and F and T are the air flow rate and the time of sampling.

Mortality Risk Assessment

The risk of mortality due to silicosis, stemming from crystalline silica exposure, was evaluated using the Mannetje model (12). This model estimates the relative risk of silicosis mortality based on cumulative exposure, presented per thousand individuals. The model accommodates cumulative silica exposure levels ranging from 0.00 to over 28.10 mg/m^3 -year.

Key inputs for the Mannetje model are the occupational exposure history and the concentration of silica (mg/m^3). Cumulative exposure to crystalline silica was calculated by multiplying the measured air concentration of crystalline silica by the duration (in years) of employment in the specific role. Subsequently, the mortality rate attributed to silicosis (per thousand individuals) was determined by referencing the provided risk assessment table (Table 1).[12]

The calculation of mortality risk because of lung cancer caused by exposure to crystalline silica was done with the formula taken from the Rice study. The following formula 2 has been used to determine the risk of mortality due to lung cancer:

$$A=0.77+373.69\times GM \tag{2}$$

That A is the lung cancer mortality rate per thousand people, and GM is the geometric mean of worker exposure to silica.[11]

Statistical Analysis

The Stata software was used to analyze all the statistical data (version 17). Frequency and relative frequency were determined for ordinal and nominal variables. Mean and standard deviation (SD) were reported for quantitative variables. The Shapiro-Wilk test was used to assess the normality of the variable distributions. Kruskal-Wallis with a post-hoc Dunn test, with adjusted P-values by the Bonferroni correction for multiple tests, and Mann-Whitney U and Chi-square tests were used to compare groups based on the desired variables. The statistical significance was set at 0.05.

Ethical Consideration

Before the study began, informed consent was obtained from all participants, and the study procedures and data collection process were fully explained to them by the researchers. Additionally, the study protocol was approved by the university's ethics committee (IR.KMU.REC.1401.124).

Table 1: Model of Mannetje (Risk assessment of mortality caused by silicosis)

Cumulative exposure to crystalline silica (mg/m^3-year)	Mortality rate in every thousand people
0-0.99	1
0.99-1.97	3.39
1.97-2.87	6.22
2.87-4.33	9.40
4.33-7.12	13.69
7.12-9.58	22.64
9.58-13.21	23.97
13.21-15.89	25.11
15.89-28.10	40.25
28.10<	63.63

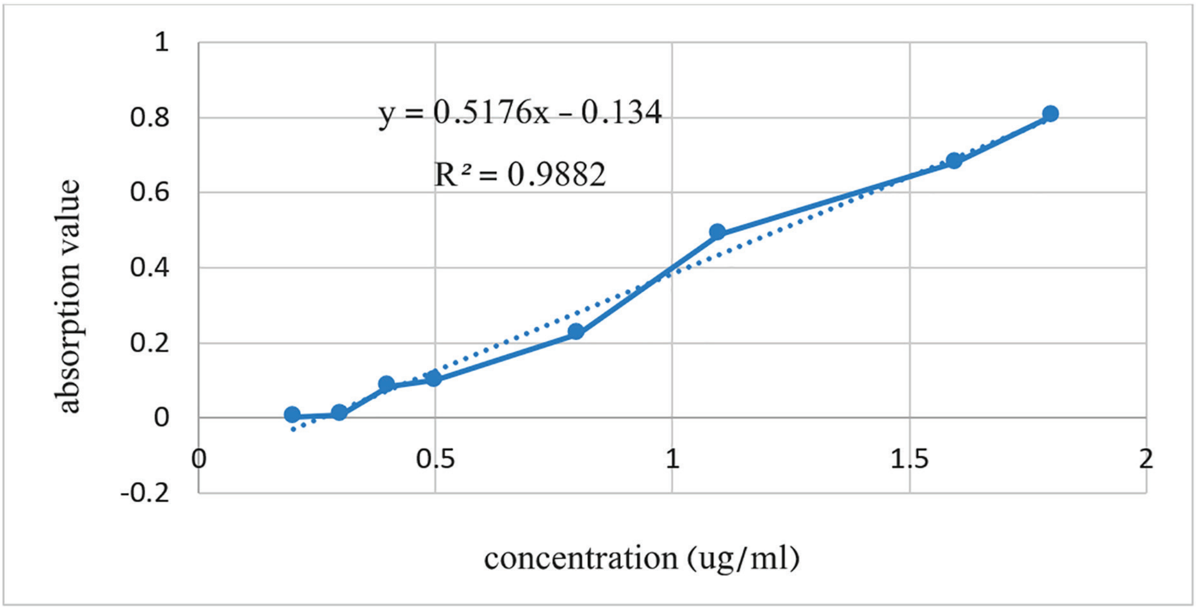

Figure 1: The obtained calibration curve for the working standards of crystalline silica

Results

People's Characteristics

All participants in this research were men. The weekly work time for the sweeper and office groups was 56 and 40 hours, respectively. The mean and standard deviation (SD) of age in the two groups were 37.66±8.79 and 37.49±3.71 years, respectively. The body mass index (BMI) was also 25.21±3.12 and 25.37±2.44 kg/m2. The work experience for the sweeper and the office group was 5.02±1.08 and 5.09±1.08, respectively. In the sweeper and office group, 9 and 60 people (7.5% and 50%) were smokers, and 100 and 102 people (83.33% and 85%) used hookah, respectively.

Calibration Curve

The absorbance values of eight working standard samples with specific silica concentrations were measured using a spectrophotometer. Subsequently, using Excel, the standard curve and the absorption-concentration equation were determined (Figure 1).

Occupational Exposure

The mean concentration of crystalline silica differed significantly between the sweeper and office groups, with sweepers exhibiting a mean of 0.67±1.40 mg/m^3 and the office group showing a mean of 0.002±0.001 mg/m^3. This difference was statistically significant ($P<0.001$) as determined by the Mann-Whitney U test. Notably, the exposure level for sweepers exceeded the Occupational Exposure Limit (OEL).

Analysis across different units within the mine revealed a significant difference in silica concentration ($P=0.003$) based on the Kruskal-Wallis test. Post-hoc multiple comparisons, adjusted with Bonferroni correction, indicated that the silica concentration in the "concentration unit" was significantly higher than in the "mill unit" ($P=0.002$) and the "raw pellet unit" ($P=0.026$). No other significant differences were found between the remaining unit comparisons.

The relative frequency of sweepers exposed to crystalline silica above the OEL was 0.93 (93%), whereas no individuals in the office group exceeded this limit. Table 2 summarizes the relative frequencies of crystalline silica exposure across various units. The highest relative frequencies were observed among sweepers in the concentration, silo, furnace, stacker, reclaimer, and screen units. Conversely, the raw pellet and mill units exhibited the lowest relative frequencies of crystalline silica exposure.

Mortality Risk Due to Silicosis

The Mannetje model was employed to assess the risk of silicosis-attributable mortality. The results, summarized in Table 3, indicate significant variations in mortality rates across the mine's units and the control office group.

The "Concentration" unit exhibited the highest mortality rate due to silicosis, estimated at 64 deaths per thousand individuals. Conversely, the "Office group," along with the "Mill" and "Silo" units, showed the lowest mortality rates, each at approximately 1 death per 1,000 individuals.

Mortality Risk Due to Lung Cancer

The Rice model was utilized to evaluate the mortality risk associated with lung cancer. The findings are presented in Table 4.

Table 2: Silica concentration and exposure higher than OEL in different units of the mine

Occupational unit	Sample number	Crystalline silica concentration	P-value*	Employees with exposure higher than the OEL	
		Mean±Std. deviation		Frequency	Relative frequency
Furnace	5	0.08±0.01	0.003	4	0.8
Concentration	7	2.54±2.18		7	1
Mill	5	0.05±0.03		4	0.8
Raw pellet	5	0.06±0.03		3	1
Screen	3	0.11±0.04		3	1
Silo	3	0.07±0.02		3	1
Stacker and Reclaimer	3	0.09±0.04		5	1

*The Kruskal-Wallis test was used to compare crystalline silica concentration between occupational units.

Table 3: Mortality risk due to silicosis by different units of the mine and groups

Occupational unit	Calculated risk value (mg/m^3-year)	Mortality rate per thousand people
Furnace	1/02	3
Concentration	50.70	64
Mill	1.28	3
Raw pellet	1.50	3
Screen	2.16	6
Silo	1.76	3
Stacker and Reclaimer	1.02	3
Sweeper (total)	1.02-50.70	3-64
Office	0.04	1

Table 4: Mortality risk due to lung cancer by different units of the mine and groups

Occupational unit	Geometric mean (mg/m^3)	Mortality range
Furnace	0.04	17.46
Concentration	1.42	534.73
Mill	0.05	19.95
Raw pellet	0.10	9.27
Screen	0.08	30.70
Silo	0.07	29.61
Stacker and Reclaimer	0.07	28.02
Sweeper (total)	0.10-1.42	9-535
Office	0.001	1

The highest risk of mortality due to lung cancer was observed in the "Concentration" unit among the sweeper group, corresponding to a geometric mean crystalline silica concentration of 1.42 mg/m^3. Conversely, the office group exhibited the lowest risk, with a geometric mean crystalline silica concentration of 0.001 mg/m^3.

Discussion

This study identified the highest concentrations of crystalline silica within the sweeper group (0.67±1.40 mg/m^3) and specifically in the "Concentration" unit (2.53±2.01 mg/m^3). Both of these values significantly exceed the permissible exposure limit (PEL) of 0.025 mg/m^3. In contrast, the office group exhibited the lowest concentration (0.002±0.001 mg/m^3), falling below the OEL. Among the mine units, the "Raw Pellet" unit recorded the lowest concentration (0.05±0.02 mg/m^3), though it still surpassed the permissible limit.

Our findings align with the study by Poormohamadi et al.,[4] which reported a range of respirable crystalline silica concentrations from 0.14 to 1.70 mg/m^3 for exposed workers, exceeding the standard level of 0.025 mg/m^3. Their study also found the lowest values in the administrative section, consistent with our observations for the office group.

The substantial difference in average crystalline silica concentrations between the sweeper and office groups can be attributed to variations in exposure frequency and intensity. The sweeper group spent the majority of their shifts in areas central to the mine's production processes, where dust generation is high. Conversely, the office group worked in environments distanced from active production lines, resulting in minimal dust exposure and concentrations below the OEL.

Differences in average crystalline silica concentrations among the various mine units are likely influenced by the frequency and duration of dust exposure within each unit, the modernity of equipment, and the specific ongoing processes. For instance, the "Concentration" unit recorded the highest exposure to crystalline silica. This can be attributed to operations such as purification and concentration, which inherently generate more dust than other processes. This finding is further supported by research conducted by Normohammadi et al.,[8] who reported silica concentrations ranging from 0.085 to 0.185 mg/m^3 levels also exceeding the permissible limit, and consistent with our research.

The silicosis mortality risk, evaluated using the Mannetje model, indicated that the highest risk was in the sweeper group, ranging from 1 to 64 per 1,000 individuals. Conversely, the lowest risk was observed in the office group, estimated at 1 per 1,000 individuals. According to OSHA standards, the acceptable threshold for this mortality risk is set at 1 per 1,000 individuals.

Our findings are consistent with the research conducted by Normohammadi et al.,[8] who reported a silicosis mortality risk ranging from 1 to 22 per 1,000 individuals, levels that also exceeded the acceptable limit. Their study further established a positive correlation between high exposure to crystalline silica and increased mortality risk, a conclusion that aligns with our results.

Among the different mine units, the "Concentration" unit exhibited the highest silicosis mortality risk, estimated at 64 per 1,000 individuals. Conversely, the "Silo," "Mill," "Furnace," "Raw Pellet," and "Stacker and Reclaimer" units displayed the lowest risk, with approximately 3 per 1,000 individuals.

The Mannetje model used for this risk assessment considers two primary factors: the average concentration of crystalline silica and the duration of employment. In this mine, the assumed working period is uniform across all individuals at 20 years. Consequently, the average concentration of crystalline silica emerges as the predominant determinant of risk levels across the studied groups and units. Our findings clearly indicate a direct correlation: groups and units with higher concentrations of crystalline silica also present higher levels of silicosis mortality risk.

This observation is consistent with the findings of Omidianidost et al.,[3] who reported a silicosis mortality risk ranging from 1 to 14 per 1,000 individuals and similarly concluded that higher silica exposure correlates with increased mortality risk.

The variations in the precise mortality risk ranges observed between our study and those previously mentioned can be attributed to several factors. These include differences in the assumed working years, the specific levels and types of crystalline silica exposure, variations in sampling and analytical methodologies for silica quantification, and distinctions in workplace environments and operational processes.

In this study, the Rice model was used to estimate the risk of lung cancer mortality. The highest risk was observed in the sweeper group, ranging from 9 to 535 per 1,000 people, while the lowest risk was found in the office group, estimated at 1 per 1,000 people. The findings of the present study are consistent with Omidianidost et al.,[3] who reported lung cancer mortality risks between 4 and 16 per 1,000 people, and concluded that risk increases with the level of exposure to the pollutant—i.e., greater silica exposure leads to higher calculated risk.

Across the mine units, the concentration unit showed the highest lung cancer risk (535 per 1,000), whereas the raw pellet unit had the lowest risk (9 per 1,000). Regarding the key parameters of the Rice model, this risk assessment mainly depends on the geometric mean of crystalline silica concentration for each group or unit. Therefore, the results of the current research highlight the need to prioritize units with higher geometric mean concentrations and reduce exposure to lower lung cancer mortality risk.

To further contextualize the results, Normohammadi et al.[8] reported a lung cancer mortality risk range of 32 to 60 per 1,000 people. Differences between mortality risk estimates across studies can be attributed to variations in the geometric mean crystalline silica concentration, which workplace characteristics, individual exposure patterns, and operational conditions may influence. In addition, Yeheyis,[19] emphasized that implementing exposure controls can reduce risk values. Overall, the body of evidence underscores the importance of reducing silica-related hazards to improve health outcomes for workers in such environments.

Future research should address several limitations identified in this study. Firstly, the impact of respirator use on silica exposure and the subsequent risk level was not assessed, leaving a gap in understanding the effectiveness of personal protective equipment. Secondly, while this study concentrated on crystalline silica as the primary pollutant, other components of mine dust may also significantly influence total mortality risk, and their effects were not evaluated. Furthermore, the potential confounding effect of smoking on mortality risk was not considered. Lastly, it is plausible that workers exhibiting abnormal blood parameters were reassigned to areas with lower contamination, which could potentially affect the accuracy of exposure-risk data and requires careful consideration in future analyses.

Conclusions

This study determined that over 93% of sweepers exceeded the Occupational Exposure Limit (OEL) for crystalline silica, whereas all office staff remained below this limit. The mortality risk associated with silicosis was highest in the sweeper group, estimated at 3–64 deaths per 1,000 people, and lowest in the office group, at 1 death per 1,000 people. Among the mine units, the concentration unit demonstrated the highest risk, while the silo, mill, furnace, raw pellet, and stacker/reclaimer units exhibited the lowest risk. Regarding lung cancer mortality, the sweeper group faced the highest risk (9–535 per 1,000), contrasted with the office group's significantly lower risk (1 per 1,000). Within the mine units, the concentration unit again showed the highest risk, and the raw pellet unit the lowest. These findings underscore the critical need to implement appropriate control methods to reduce occupational exposures and associated risks to acceptable levels, thereby improving worker health and safety.

Authors' Contribution

Haniyeh Soltanpour: Conceptualization, Data collection, Result interpretation, Writing - original draft, Visualization; Ali Faghihi Zarandi: Resources, Writing - review & editing; Abdollah Gholami: Methodology, Result interpretation, Writing - review & editing; Saiedeh Haji-Maghsoudi: Methodology, Data analysis, Writing - review & editing; Behnam Khodarahmi: Conceptualization, Data collection, Supervision; Rouhollah Parvari: Conceptualization, Methodology, Funding acquisition, Supervision, Result interpretation, Writing - review & editing

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Conflict of Interest

The authors declare no potential competing interests.

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