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RESEARCH ARTICLE

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Occupational exposure to respirable crystalline silica among US metal and nonmetal miners, 2000–2019

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Abstract

Background: In metal and nonmetal (M/NM) mines in the United States, respirable crystalline silica (RCS) exposures are a recognized health hazard and a leading indicator of respiratory disease. This study describes hazardous exposures that exceed occupational exposure limits and examines patterns of hazardous RCS exposure over time among M/NM miners to better inform the need for interventions.

Methods: Data for this study were obtained from the Mine Safety and Health Administration (MSHA) Open Government Initiative Portal for the years 2000–2019, examining respirable dust samples with MSHA-measured quartz concentration >1%. Descriptive statistics for RCS were analyzed for M/NM miners by year, mine type, sector, commodity, occupation, and location in a mine.

Results: This study found the overall geometric mean (GM) for personal exposures to RCS was 28.9 μg/m^3 (geometric standard deviation: 2.5). Exposures varied significantly by year, mine type, sector, commodity, occupation, and location in a mine. Overall, the percentages of exposures above the MSHA permissible exposure limit (PEL for respirable dust with >1% quartz, approximately 100 μg/m^3 RCS) and the National Institute for Occupational Safety and Health RCS recommended exposure limit (REL, 50 μg/m^3) were 11.8% and 27.3%, respectively. GM exposures to RCS in 2018 (45.9 μg/m^3) and 2019 (52.9 μg/m^3) were significantly higher than the GM for all years prior. The overall 95th percentile of RCS exposures from 2000 to 2019 was 148.9 μg/m^3, suggesting a substantial risk of hazardous exposures above the PEL and REL during the entire period analyzed.

Conclusions: The prevalence of high exposures to RCS among M/NM miners continues in the past 20 years and may be increasing in certain settings and occupations. Further research and intervention of the highest exposures are needed to minimize the risks of acquiring silica-induced respiratory diseases.

KEYWORDS

metal and nonmetal mining, quartz, respirable dust, silica

1 | INTRODUCTION

In industrial settings, exposure to respirable crystalline silica (RCS), also commonly known as silica, silica dust, or quartz, is a prevalent, widely recognized, and persistent occupational hazard. Silica exposure is one of the oldest known occupational exposures and is estimated to affect 2 million workers in the construction industry and 300,000 workers in other industries (e.g., brick manufacturing, foundries, and hydraulic fracturing) within the United States.[1] Classified as a human carcinogen,[2] silica exposure can also cause silicosis and is associated with the development of chronic obstructive pulmonary disease, lung cancer, airway diseases, and chronic renal disease.[3,4] These diseases have long latency, but even short-term exposure (i.e., weeks or months) to RCS at very high levels can trigger acute silicosis.[5] While silicosis is neither treatable nor reversible, it is preventable by limiting workers' exposures to respirable silica dust.[6]

Quartz is the most common mineral in the earth's crust, and as such, exposures to RCS are prevalent in the mining industry. Mine workers may be exposed to RCS during the extraction, processing, and transportation of silica-containing materials (e.g., stone, sand, gravel, etc.). Certain mining-related activities and occupations are known to have hazardous exposures to RCS, for example, rock drilling, grinding, and dredging activities and mining machine operator occupations.[3]

Since quartz (silica) can never be eliminated or substituted for in the metal and nonmetal (M/NM) mining industry, under the National Institute for Occupational Safety and Health (NIOSH) hierarchy of controls, engineering controls, administrative controls, and personal protective equipment should be applied, in that order, to control silica hazards in the mining work environment.[7] Some commonly used engineering controls for dust are filters, whole mine and general dilution ventilation, local exhaust ventilation, wet suppression practices, operator booths, barriers, control rooms, enclosed cabs, enclosures at dust emission source points, and clothes cleaning systems.[8–10]

There is ample evidence from various industries, such as diatomaceous earth mining and processing[11] or engineered stone fabrication[12] that silica overexposure causes respiratory and autoimmune diseases, including fatal outcomes. Previous respirable silica dust research has signified the potential for respiratory illness with acute, accelerated, and chronic exposures. The risk of chronic disease, including chronic silicosis and lung cancer, is often determined by the "cumulative exposure to an occupational stressor".[13] Steenland and Brown[14] in a large study among 3330 gold miners found the risk of silicosis increased from 1% for those with cumulative exposure less than 0.5 mg/m^3 years to 68%–84% for those miners with more than 4 mg/m^3 years of exposure.

The Mine Safety and Health Administration (MSHA) is the regulatory agency that promulgates standards and permissible exposure limits (PELs), conducts mine health and safety compliance inspections, and provides technical and educational support to mining operations.[15] The Coal Workers' Health Surveillance Program (CWHSP), established by the Federal Coal Mine Health and Safety Act of 1969, tracks respirable diseases attributable to coal mine dust exposures.[16] Administered by NIOSH, the CWHSP is a federally funded national medical surveillance program for coal miners that offers chest radiographs, periodic spirometry, and respiratory health questionnaires, and provides confidential and free-of-charge reporting on miners' health status from NIOSH-approved clinics.[17] The program has been effective at observing increases in the prevalence of coal workers' pneumonoconiosis and progressive massive fibrosis in Appalachia concurrent with changing coal mining conditions and practices.[18] There is no comparable program available to M/NM miners, and little is known about their rates of respiratory disease.

Related to silica exposures in M/NM mining in the US, previous studies using MSHA's health inspection data, published in 1995, 2006, and 2012 show silica overexposures continue to occur, defined by regulatory and recommended occupational exposure limits.[19–21] All three studies indicate hazardous silica exposures in several mine worker occupations, including stone polishers and baggers, and mining activities such as crushing and ore processing, and in all noncoal mining industry subsectors (metal, nonmetal, stone, sand, and gravel).

As previous research indicates, excessive silica exposure is prevalent in the mining industry.[8,14-17,22-26] The most recent study investigating silica exposures in M/NM mines and mills[21] examined data for 1974–2010 and found hazardous exposures persist. Separately, Cauda et al.[24] analyzed the percent quartz (pQ) in MSHA respirable dust samples for 1997–2011 as a potential exposure determinant and reported it was higher in surface locations than underground, and higher in sand and gravel mines than in other M/NM mines. To determine whether there have been changes in silica exposures, particularly after 2010, our current study examines silica exposures by occupation, mine type, location, and year among all M/NM mines sampled by MSHA for contaminant code 523, "Quartz (Crystalline Silica) - SiO_2 (Respirable)," during 2000–2019. This study is intended to increase the understanding of past and recent silica exposures in the M/NM and provides an update to inform public health decision-making as well as research and intervention needs.

2 | METHODS

2.1 | Occupational exposure limits

The Occupational Safety and Health Administration (OSHA) and MSHA PELs were based on the 1973 American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit values (TLVs®),[27] which MSHA's predecessor agency, the Mine Enforcement Safety Administration adopted in 1974.The 1973 ACGIH TLV® limits the level of respirable dust containing ≥1% quartz and is calculated in mg/m^3 for each personal breathing zone sample based on the pQ in the respirable dust sample.[28,29] MSHA does not have a PEL specific to RCS. On the basis of 1973 ACGIH TLV®, the PEL is for respirable dust containing crystalline silica, and the PEL is proportionally reduced as the crystalline silica content (pQ) of the sampled dust increases. The calculated respirable dust TLV® or PEL is reduced by one-half if the (rare) silica forms cristobalite and tridymite are present, but that information was not available for the data used in this study. A sample-specific exposure limit for quartz-containing respirable dust) is calculated for each sample found to have ≥1 "pQ" by weight, shown as

$$\text{sample-specific TLV® and PEL mg/m}^3 = (10) \\ /(\text{percent quartz in the respirable dust sample} + 2). \tag{1}$$

The TLV and PEL lower and upper bounds are 0.10 and 3.33 mg/m^3, for dust containing a maximum of 100% quartz and a minimum of 1% quartz, respectively.

In 1974, NIOSH established a recommended exposure limit (REL) for RCS of 50 µg/m^3 as a time-weighted average (TWA) for up to 10 h a day for a 40-h workweek.[30] In 2016, OSHA released a silica final rule for the construction industry with a PEL of 50 µg/m^3 for an 8-h TWA.[1] ACGIH lowered its TLV for crystalline silica to 25 µg/m^3 in 2006.[31] To allow comparison with modern occupational exposure limits, like the REL and the current ACGIH TLV, it is necessary to backcalculate the sample's RCS concentration using the MSHA-calculated sample-specific respirable dust PEL and the respirable dust concentration. The RCS (as quartz, "Q") concentrations were obtained using Equation (2). The RCS concentrations were compared to the PEL, which is approximately equal to an 8-h TWA RCS (quartz) limit of 100 µg/m^3, and the NIOSH REL for RCS

$$\text{RCS} \quad \mu\text{g/m}^3 = 10\left(\frac{10}{\text{sample-specific dust PEL}} - 2\right) \\ \times (\text{concentration of respirable dust}). \tag{2}$$

Since MSHA does not include the personal breathing zone respirable dust samples' measured pQ in the public dataset, we back-calculated (solved for) pQ from MSHA data using the 1973 ACGIH TLV formula, as shown in Equation (3). The methods have been previously discussed[20]

$$\text{pQ\%} = \left[\left(\frac{10}{\text{sample-specific dust PEL}}\right)\text{-}2\right]. \tag{3}$$

When the ratio of TWA respirable dust concentration to TLV is greater than 1.0, the sample exceeds the 1973 ACGIH TLV®. MSHA currently applies an "error factor" (one-sided correction factor) to the TWA/PEL ratio, based on the upper 95% confidence limit of the combined sampling and analytical error. The TWA/PEL ratio must exceed 1.2 to be classified as an exceedance by MSHA.[32] Consistent with the 1973 TLV and the industrial hygiene principle that the best estimate of the worker's TWA is the measured value, and the TWA/exposure limit ratio is calculated without adjustment, we did not implement MSHA's correction factor.

2.2 | Respirable dust data

From the publicly available MSHA datasets, two separate data sources from 2000 to 2019 were used for this study. The *Personal Health Samples* (PHS) is the primary dataset (accessed February 25, 2021, from MSHA's Open Government Initiative Portal) and contained the respirable dust measurements with MSHA-measured quartz concentrations >1%.[33] Specifically, only M/NM records that were personal breathing zone samples collected on individual workers during their work shifts (personal samples) with MSHA contaminant code 523 —"Quartz, respirable, >1% Qtz"—were used in all analyses. "Respirable Crystalline Silica (RCS)" or "silica" in this study refers to MSHA's contaminant code 523 data. The 1973 TLV® and resulting PEL apply only to samples with >1% quartz, and pQ and RCS concentrations can only be back-calculated from them. Personal sample records for dissimilar types of respirable dust, including contaminant codes 121 ("Nuisance dust, respirable, <1% quartz) and 131 ("Unlisted particulate, respirable, <1% Quartz") were not used. The PHS dataset includes, per sample, the following variables: respirable dust concentration (mg/m^3), sample-specific PEL (mg/m^3), concentration/exposure limit ratio including MSHA's correction factor, mine identification number, sample number, date of sample collection, event number, contaminant description, contaminant code, location in the mine, primary commodity mined, state, and job title, among other exposure factors.

The *Mines* dataset (accessed February 25, 2021, from MSHA's Open Government Initiative Portal) includes explanatory information about the status of, and employment in, all mines reported to MSHA by mine operators.[34] Certain explanatory variables from the *Mines* dataset were utilized, such as the unique mine identification number, current mine type, primary canvass, and primary Standard Industrial Classification (SIC) code (primary commodity extracted at mine). The unique mine identification number was used to merge the *PHS* dataset with the *Mines* dataset.

The back-calculated pQ values are equivalent to percent silica, assuming the rare tridymite and crystallite forms are not present and are reported in our results as "% silica" (pQ). The *PHS* dataset identified 57,712 respirable quartz-containing dust measurements collected between 2000 and 2019. Derived from the 1973 ACGIH TLV® formula (shown in Equation 1), the sample-specific respirable dust TLV and PEL vary with the percent silica in the dust, and the lower and upper bounds for the TLV and PEL for respirable dust are 0.10 and 3.33 mg/m^3. These bounds are derived from Equation (1) for a sample with 100 and 1 pQ in the dust (the maximum and minimum percent), respectively.[20,28] Of the 57,712 dust samples with MSHA-calculated PELs, 2288 were below the lower bound and 64 were above the upper bound. Samples with PELs outside the lower or upper bounds ($n = 2352$) and those in which the concentration of respirable dust equaled 0 mg/m^3 ($n = 3$) were excluded as erroneous.

Samples with a back-calculated RCS concentration of less than 5 µg/m^3 were excluded ($n = 17$) because the MSHA P-2 analytical method for RCS has a method detection limit of 5 µg/m^3.[35] Duplicates found with an exact match on seven variables (concentration, exposure_limit, mine_id, event_no, sample_date, job_cd_desc, and primary_canvass) and confirmed by the MSHA Pittsburgh Safety and Health Technology Center ($n = 74$) were excluded.

Samples classified as “Quartz >1% Respirable Fraction” that had less than 1% quartz were excluded after confirmation by MSHA ($n = 1$). Overall, 2447 samples were excluded, and 55,265 quartz (crystalline silica) samples (96%) were retained for analysis. Samples ($n = 37$) with an extremely high respirable dust concentration, >10 mg/m^3 were examined for possible errors. Two of these records were manually corrected after a discussion with MSHA, the remainder were validated.

2.3 | Statistical analysis

Descriptive statistics were calculated for the entire cross-section of workers sampled for RCS to determine if personal exposures measured during compliance inspections have changed over time and then classified by year, mine type, sector, commodity, occupation, and location in a mine. Statistical parameters calculated were arithmetic mean (AM), geometric mean (GM), geometric standard deviation (GSD), and percent of the samples collected for a particular group that are over the PEL or REL (hereafter referred to as exceedance fractions). The mean back-calculated pQ was also reported for the RCS samples. The Kolmogorov–Smirnov test indicated that the overall data distribution was significantly different than a normal distribution ($p < 0.001$). However, a log-probability plot confirmed that the data distribution was approximately log-normal. A one-way analysis of variance conducted through a general linear model was performed for all explanatory variables using log-transformed RCS data to determine if any group differed significantly from the overall group mean. All analyses and graphics were conducted using SAS (Version 9.4, SAS Institute) or Rstudio (Version 1.1.453, Rstudio Team (2020), *Rstudio: Integrated Development for R*. Rstudio, PBC).

3 | RESULTS

3.1 | Summary statistics

In this study, we analyzed 55,265 RCS measurements collected by MSHA at 10,263 M/NM active mines in the 50 states, Puerto Rico, and the Virgin Islands from 2000 to 2019. Table 1 presents silica exposure statistics, including PEL and REL exceedance fractions, arithmetic and GMs, and GMs for percent silica by year, for 20 years. Across the entire 20-year period, 11.8% of the RCS samples exceeded the PEL, and 27.3% of the back-calculated RCS exposures exceeded the NIOSH REL. The overall AM, GM, and GSD of RCS exposures were 47.8 μg/m^3, 28.9 μg/m^3, and 2.5, respectively, with a range of 4340.8 μg/m^3. The overall median was 26.9 μg/m^3 and the 95th percentile was 148.9 μg/m^3. The highest RCS exposure (4346.4 μg/m^3) was measured for a laborer/bullgang worker in a mill at a stone mine.

Overall, a simple linear regression of the log-transformed RCS concentrations ($n = 55{,}265$) versus the sampling year showed no trend. The slope ($\beta = 0.0059$) of the regression line was statistically significant ($p < 0.0001$), but the overall $R^2 = 0.001$ denoted that very little of the variance was accounted for by the regression model. Figure 1 shows annual RCS exceedance fractions for the MSHA PEL and NIOSH REL. Over the 20 years, the annual exceedance fraction for the MSHA PEL ranged from 6.9% to 17.3%, with no observed trend in either direction. Similarly, the annual sample exceedance fraction for the NIOSH REL ranged from 21.7% to 46.3%, with the maximum occurring in 2019, the last year of the study period.

The number of RCS (contaminant code 523) samples collected in 2018 and 2019 was substantially less than in all years from 2000 to 2017, and these two years had significantly higher AM and GM exposures than all previous years. Figure 2 shows the distribution of the number of samples per mine. Over the 20-year period, 2841 (27.7%) of 10,263 mines had only one sample collected for dust containing >1% quartz, and for this period, MSHA collected less than 10 samples for RCS (contaminant 523) in 86% of all M/NM mines that were sampled.

3.2 | Mine type, industry subsector, and commodity

The 55,265 RCS measurements collected by MSHA were collected in three general mine types (as classified by MSHA): 86.9% were in surface mines; 7.4% were in surface facilities (milling and processing), and 5.7% were in underground mines. These proportions are approximately consistent with the respective proportions of active mining operations. By mine type, the GM exposures were judged to be not meaningfully different (defined as >10% difference), although the differences were all statistically significant ($p < 0.0001$). Surface mines had an AM exposure of 47.6 μg/m^3 and GM exposure of 28.9 μg/m^3, surface facilities had an AM exposure of 49.8 μg/m^3 and GM exposure of 29.8 μg/m^3, and underground mines had an AM of 47.8 μg/m^3 and GM exposure of 27.6 μg/m^3.

Four mining industry subsectors (“metal,” “nonmetal,” “stone,” and “sand and gravel”), defined by MSHA Canvass Codes (associated with primary commodity, also known as the industry group code) based on the six-digit SIC codes were represented in the data. Among all samples, 50.2% were taken from stone mines, 31.8% from sand and gravel mines, 11.4% from (other types of) nonmetal mines, and 6.5% from metal mines. Metal mines (AM: 62.6, GM: 36.8 μg/m^3) and nonmetal mines (AM: 61.9, GM: 36.2 μg/m^3) had markedly higher AM and GM exposures compared to stone mines (AM: 44.5, GM: 26.8 μg/m^3) and sand and gravel mines (AM: 44.7, GM: 28.5 μg/m^3). Despite these differences in mean exposures, the variability of RCS exposures among the subsectors was quite similar (GSD 2.4–2.6).

TABLE 1 Respirable crystalline silica exposures, by year, among metal and nonmetal mines, MSHA, 2000–2019

Year	*N*	% > PEL	% > REL	GM % silica	AM (µg/m^3)	95th (µg/m^3)	GM (µg/m^3)	GSD	95% CL of GM lower limit (µg/m^3)	95% CL of GM upper limit (µg/m^3)
2000	1118	6.9	26.9	7.8	44.7	114.5	28.2	2.4	26.8	29.7
2001	3155	11.0	28.4	7.9	46.5	132.5	29.3	2.5	28.4	30.2
2002	3801	11.3	27.0	7.8	47.0	148.9	29.1	2.5	28.2	29.9
2003	4554	12.0	25.6	7.0	46.7	151.7	27.2	2.6	26.4	27.9
2004	5210	11.9	26.2	7.6	45.9	148.4	27.6	2.6	26.9	28.3
2005	4944	12.5	27.5	7.7	49.2	159.4	28.8	2.6	28.0	29.6
2006	2555	17.3	34.2	8.1	61.6	187.7	34.2	2.7	32.9	35.6
2007	2702	14.4	30.3	7.7	51.4	155.6	30.7	2.6	29.6	31.8
2008	2083	16.3	32.9	7.5	55.0	172.1	32.8	2.6	31.5	34.2
2009	4023	10.5	24.1	7.7	44.7	132.2	26.6	2.5	25.8	27.3
2010	3386	9.7	22.8	7.9	43.0	127.8	25.7	2.5	24.9	26.5
2011	2758	10.5	23.9	8.0	43.7	141.8	26.6	2.5	25.7	27.5
2012	2370	11.5	25.6	8.2	44.4	140.3	27.7	2.5	26.7	28.7
2013	1943	8.9	21.7	7.5	40.0	120.7	25.3	2.4	24.3	26.3
2014	2029	10.0	23.9	8.0	43.3	133.8	26.7	2.5	25.7	27.8
2015	2035	11.0	24.9	8.4	45.5	142.1	27.4	2.5	26.3	28.5
2016	1878	10.4	25.9	8.9	44.8	133.0	27.9	2.5	26.8	29.1
2017	2326	10.9	27.0	8.5	47.3	147.2	28.9	2.5	27.9	30.0
2018	1228	14.7	42.4	12.3	61.8	159.6	45.9	2.1	44.0	47.8
2019	1167	16.3	46.3	12.6	68.1	178.5	52.9	1.9	51.0	54.9

Abbreviations: 95th, 95th percentile; AM, arithmetic mean; CL, confidence limit; GM, geometric mean; GSD, geometric standard deviation; MSHA, Mine Safety and Health Administration; *N*, number of samples; % > PEL, % of samples greater than permissible exposure limit; % > REL, % of samples greater than recommended exposure limit.

There were 100 different mined commodities across all RCS personal samples collected by MSHA. Overall, the commodities where workers were most frequently sampled were "construction sand and gravel" at 30.9% and "crushed and broken limestone NEC (not elsewhere classified)" at 23.9%. The other 45.2% of the samples were in the other 98 commodities (of the 100 commodities). Table 2 shows that after restricting the analysis to commodities with at least 100 personal samples, quartz, ground (surface mine type) and gold ore (facility mine type) had the highest GM exposures, 75.7 µg/m^3 and 74.8 µg/m^3, respectively, with the former having the highest percent silica, 31.7%, in the analysis.

3.3 | Occupation

MSHA's 2006 M/NM Health Inspection Procedures Handbook instructs inspectors to target "high risk" occupations, with an emphasis on several exposure factors, including the nature of the contaminant, proximity to the contaminant source, number of potentially exposed miners, and type of work occurring.[36] Over the 20 years of observed data, 115 different MSHA-defined occupations were sampled for RCS at least once among the sampled mines. Most (79%) of the personal RCS samples were among only 11 of these occupations (crusher operator/worker; front-end loader operator; laborer, bullgang; truck driver; utility man; bagging operator; cleanup man; stone polisher/cutter; mechanic; dry screen plant operator; and bulldozer operator). Of the 11 most-sampled occupations, crusher operators and front-end loader operators were the most frequently sampled, comprising 35% of all M/NM samples, with crusher operators sampled in all mine types, but nearly all were in stone mines (53.2%) and sand and gravel mines (37.7%).

Box and whisker plots of the exposures for the 11 most-sampled occupations are shown in Figure 3, with the median (50th percentile) marked by a horizontal line, the box bounded by the 25th and 75th percentiles, and the highest individual exposures by occupation, greater than the 95th percentile values. All of these 11 occupations had measured exposures several orders of magnitude above the respective AM and GM exposure levels.

Table 3 shows exposures for the 23 occupations with at least 250 samples. Among the 11 occupations previously mentioned, the

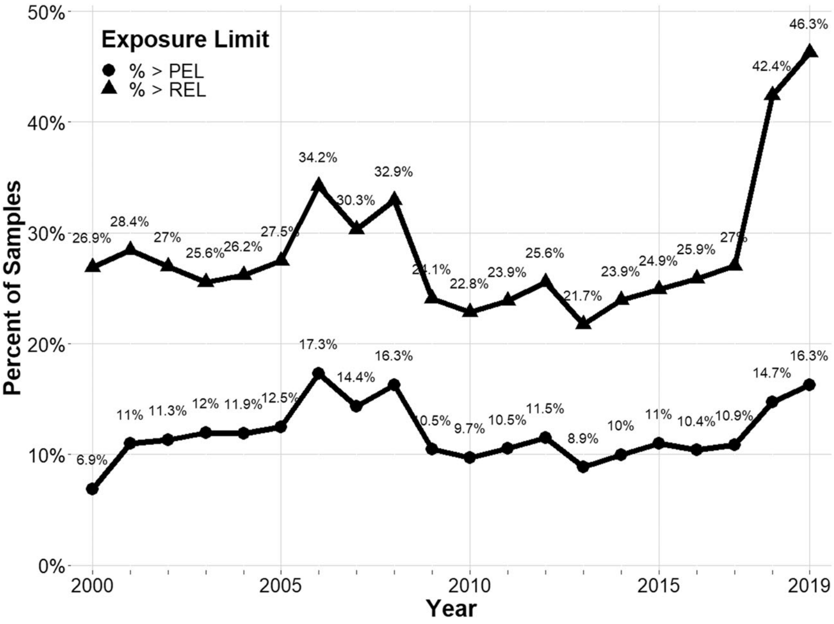

FIGURE 1 Annual respirable crystalline silica exceedance fractions (%) for all samples for the Mine Safety and Health Administration (MSHA) PEL and National Institute for Occupational Safety and Health REL. MSHA, 2000–2019. PEL, permissible exposure limit; REL, recommended exposure limit.

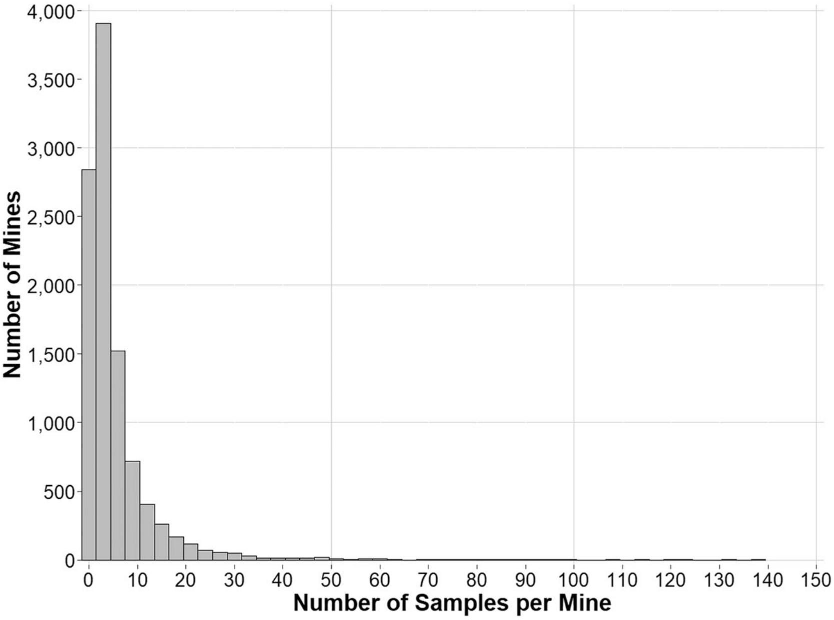

FIGURE 2 Number of samples for respirable dust with >1% quartz per mine among metal and nonmetal mines. Mine Safety and Health Administration, 2000–2019.

AM exposures ranged from 29.7 to 89.1 μg/m^3; the 95th percentile was highest for stone polisher/cutter at 284.5 μg/m^3, bagging operator at 199.9 μg/m^3, laborer/bullgang at 179.9 μg/m^3, the cleanup man at 178.7 μg/m^3, and dry screen plant operator at 155.2 μg/m^3. Only front-end loader operators and truck drivers were below 100 μg/m^3. Overall, the GSDs for the 11 occupations indicate typical within-group variability (2.2–2.6). Stone polisher/cutter had the highest mean exposure, with a GM of 56.7 μg/m^3, and 27.2% of the exposures exceeded the PEL and 57.3% exceeded the REL. Several of these highly sampled occupations involve grinding, cutting, and packing materials in surface mines. For the remaining 12 occupations, GM exposures ranged from 22.0 (washer operator) to 54.2 μg/m^3 (jackhammer operator), and exceedances for the PEL ranged from 5.9% (backhoe operator) to 29.1% (jackhammer operator). Furthermore, exceedances for the REL ranged from 15.0% (washer operator) to 50.4% (jackhammer operator).

Figure 4 is a scatterplot showing the average frequency of sampling per year versus the 20-year GM RCS concentration by occupation for all occupations ($n = 53$) with at least 50 samples. Overall, by occupation, there is no association between GM RCS exposure and annual sampling frequency ($p = 0.87$, $R^2 = 0.0005$). However, over the 20 years, several of the most frequently sampled occupations (crusher operator/worker, front-end load operator, and truck driver) were consistently among the occupations with the lower mean exposures to RCS. By contrast, certain occupations (bagging operator, stone polisher/cutter, cutting machine helper, and jackhammer operator) with the highest GM RCS exposures, all with exceedance fractions ≥20% for the REL, were sampled relatively infrequently.

TABLE 2 Respirable crystalline silica exposures by primary commodity[a] by mine type (*n* > 100), among metal and nonmetal mines, MSHA, 2000–2019

Mine type	Commodity	*N*	% > PEL	% > REL	GM % silica	AM (μg/m³)	95th (μg/m³)	GM (μg/m³)	GSD	95% CL of GM lower limit (μg/m³)	95% CL of GM upper limit (μg/m³)
Facility	Cement	1225	9.7	16.8	3.3	31.9	94.9	21.4	2.3	20.4	22.4
	Sand, industrial NEC	372	19.9	48.7	12.5	69.1	223.2	49.3	2.2	45.5	53.4
	Bentonite	239	19.2	37.2	5.1	49.8	135.2	37.5	2.2	34.0	41.4
	Barite barium ore	219	8.2	16.0	3.9	30.8	98.2	21.6	2.2	19.4	24.0
	Iron ore	216	15.7	30.6	9.8	55.7	196.2	33.3	2.7	29.2	38.0
	Crushed, broken limestone NEC	205	15.1	22.4	4.2	37.6	123.4	23.7	2.5	20.9	26.9
	Gold ore	183	39.3	65.6	16.8	114.0	383.9	74.8	2.4	65.7	85.1
	Common clays NEC	143	9.8	21.0	3.9	40.6	163.5	21.6	2.7	18.3	25.5
	Crushed, broken stone NEC	117	16.2	45.3	14.5	61.6	198.2	40.4	2.5	34.0	48.0
	Ground silica	111	27.0	62.2	19.5	92.3	279.4	66.0	2.3	56.6	77.0
Surface	Construction sand and gravel	17,007	9.9	25.0	9.7	44.5	134.6	28.4	2.4	28.1	28.8
	Crushed, broken limestone NEC	11,560	6.5	16.0	5.2	32.1	91.2	20.8	2.3	20.5	21.1
	Crushed, broken granite	2735	7.8	25.1	9.3	41.7	116.6	28.8	2.3	28.0	29.7
	Crushed, broken stone NEC	2724	10.8	26.9	7.7	47.5	159.6	28.7	2.5	27.7	29.7
	Dimension stone NEC	1834	23.5	47.7	14.4	81.2	270.3	48.8	2.7	46.7	51.0
	Crushed, broken sandstone	1299	17.9	46.1	15.2	68.0	200.2	45.1	2.4	43.0	47.3
	Sand, industrial NEC	1137	21.0	44.2	14.8	77.9	261.3	44.0	2.7	41.5	46.6
	Crushed, broken traprock	925	12.2	24.0	6.5	41.6	125.5	26.3	2.5	24.8	27.9
	Dimension sandstone	867	24.9	57.3	18.6	86.2	246.4	57.2	2.4	53.9	60.6
	Common clays NEC	760	11.8	29.5	6.6	45.5	127.0	30.2	2.4	28.4	32.1
	Dimension slate	669	26.8	58.6	18.6	83.9	253.4	58.4	2.3	54.8	62.2
	Dimension limestone	652	11.2	25.9	5.7	43.1	126.1	26.7	2.5	24.8	28.7
	Copper ore NEC	639	17.8	36.0	10.2	74.9	241.8	37.5	2.7	34.7	40.5
	Iron ore	578	19.2	42.6	10.7	61.2	172.7	40.5	2.5	37.6	43.6
	Gold ore	548	16.4	37.6	10.4	60.7	168.1	37.1	2.5	34.3	40.1
	Sand, common	442	10.4	27.6	10.3	50.7	185.8	28.3	2.7	25.8	31.0
	Ground silica	402	29.6	63.2	25.2	95.1	302.1	61.5	2.6	56.0	67.5
	Common shale	401	18.5	36.7	8.5	54.6	149.1	35.9	2.4	32.9	39.2
	Dimension granite	392	18.1	32.7	10.9	71.2	302.6	36.2	2.9	32.5	40.2
	Clay, ceramic, refractory minerals	261	16.5	33.3	7.1	48.7	132.8	34.3	2.3	31.0	37.9
	Cement	234	6.4	13.7	3.3	27.2	76.3	20.0	2.1	18.1	22.0
	Crushed, broken slate	143	30.8	50.3	13.2	89.4	296.4	55.1	2.7	46.9	64.9

(Continues)

TABLE 2 (Continued)

Mine type	Commodity	*N*	% > PEL	% > REL	GM % silica	AM (μg/m^3)	95th (μg/m^3)	GM (μg/m^3)	GSD	95% CL of GM lower limit (μg/m^3)	95% CL of GM upper limit (μg/m^3)
	Gypsum	131	1.5	6.9	4.0	20.2	63.8	15.3	2.0	13.6	17.2
	Crushed, broken quartzite	121	34.7	61.2	21.2	113.9	419.6	66.8	2.9	55.1	80.9
	Quartz, ground	114	42.1	70.2	31.7	123.1	434.6	75.7	2.8	62.7	91.4
	Miscellaneous nonmetallic minerals NEC	109	24.8	33.0	3.4	44.0	120.7	30.3	2.4	25.7	35.8
Underground	Crushed, broken limestone NEC	1450	8.1	16.5	3.6	34.6	96.1	22.2	2.3	21.2	23.2
	Gold ore	478	18.0	35.8	6.4	58.2	171.3	37.6	2.4	34.7	40.7
	Molybdenum ore	231	13.9	40.7	8.3	48.8	122.1	36.8	2.2	33.3	40.8
	Sand, industrial NEC	206	35.9	53.9	14.4	136.4	437.0	66.0	3.1	56.6	76.9

Abbreviations: 95th, 95th percentile; AM, arithmetic mean; CL, confidence limit; GM, geometric mean; GSD, geometric standard deviation; MSHA, Mine Safety and Health Administration; *N*, number of samples; NEC, not elsewhere classified; % > PEL, % of samples greater than permissible exposure limit; % > REL, % of samples greater than recommended exposure limit.

[a] This variable is identified as "primary_sic" in the *Personal Health Samples* dataset.

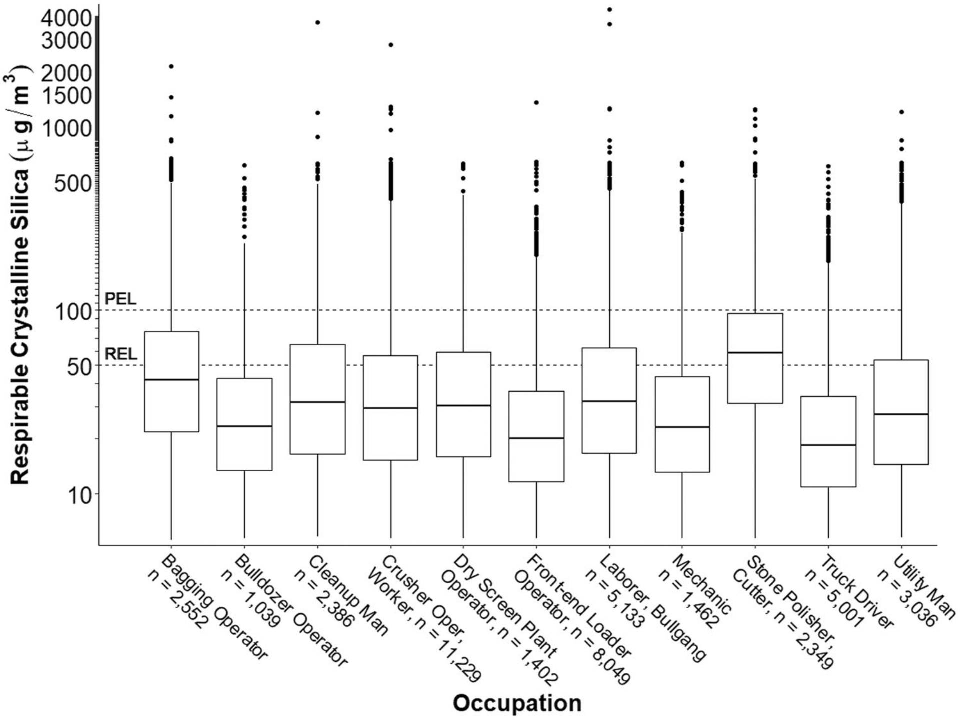

FIGURE 3 Respirable crystalline silica (RCS) exposures for occupations with *n* > 1000 RCS samples among metal and nonmetal mines. Mine Safety and Health Administration 2000–2019. PEL, permissible exposure limit; REL, recommended exposure limit.

3.4 | Mine location

There were 36 MSHA-classified worker locations and processes. Approximately half of all exposure measurements were collected in one of three locations: active production in surface mines (*n* = 13,352), ore processing in surface mines (*n* = 8524), and crushing in mills (*n* = 6149). Table 4 shows mine locations with >1000 RCS samples; the highest GM exposures were in bagging (40.7 μg/m^3) and dry screening (35.9 μg/m^3). Among locations with <1000 samples (not shown), the highest GM exposures were found in

TABLE 3 Respirable crystalline silica exposures by occupation[a] ($n > 250$), all mine types, among metal and nonmetal mines, MSHA, 2000–2019

Occupation	*N*	% > PEL	% > REL	GM % Silica	AM (µg/m^3)	95th (µg/m^3)	GM (µg/m^3)	GSD	95% CL of GM lower limit (µg/m^3)	95% CL of GM upper limit (µg/m^3)
Crusher oper/worker	11,229	12.2	29.2	8.2	48.9	153.1	30.6	2.5	30.1	31.1
Front-end loader operator	8049	5.2	16.4	7.5	31.6	89.7	21.7	2.2	21.3	22.1
Laborer, bullgang	5133	15.0	32.6	8.3	56.1	179.9	33.5	2.6	32.6	34.4
Truck driver	5001	4.8	13.7	6.1	29.7	83.2	20.5	2.2	20.0	20.9
Utility man[b]	3036	12.4	27.6	7.9	49.3	152.4	29.5	2.5	28.6	30.5
Bagging operator	2552	21.4	42.5	7.4	66.0	199.9	41.2	2.5	39.8	42.7
Cleanup man	2386	16.8	33.4	8.1	57.3	178.7	33.8	2.6	32.5	35.1
Stone polisher/cutter[b]	2349	27.2	57.3	14.8	89.1	284.5	56.7	2.6	54.6	58.9
Mechanic	1462	9.6	21.3	7.1	39.9	119.1	25.1	2.4	24.0	26.3
Dry screen plant operator	1402	13.8	30.6	8.6	51.0	155.2	32.0	2.5	30.5	33.6
Bulldozer operator	1039	7.3	20.2	8.4	38.6	110.3	25.3	2.3	24.0	26.6
Backhoe operator	852	5.9	17.4	8.5	33.2	97.3	22.7	2.3	21.4	23.9
Supervisor, Co. Official	820	7.0	20.9	8.7	38.6	121.5	25.0	2.4	23.6	26.5
Washer operator	788	6.1	15.0	8.6	33.5	98.1	22.0	2.3	20.7	23.2
Kiln/dryer operator	752	16.9	37.1	10.3	66.4	229.2	38.7	2.6	36.1	41.4
Drill operator, rotary air[b]	693	12.0	27.1	7.5	48.7	153.0	28.6	2.6	26.6	30.7
Drill operator, rotary[b]	672	8.6	21.4	6.3	38.8	108.6	24.4	2.4	22.8	26.1
Ball mill operator	471	17.0	38.9	9.3	66.6	219.9	38.3	2.7	35.0	41.9
Bobcat operator	460	14.1	34.1	9.8	61.7	201.4	35.2	2.6	32.3	38.4
Forklift operator	429	13.3	31.0	8.5	49.6	154.7	30.4	2.6	27.8	33.2
Lab technician	341	17.0	37.5	11.4	69.2	224.5	38.3	2.7	34.4	42.6
Truck loader	287	13.2	30.7	8.9	49.4	160.4	31.4	2.5	28.2	34.9
Jackhammer operator	268	29.1	50.4	13.2	100.7	389.8	54.2	2.9	47.6	61.7

Abbreviations: 95th, 95th percentile; AM, arithmetic mean; CL, confidence limit; GM, geometric mean; GSD, geometric standard deviation; MSHA, Mine Safety and Health Administration; *N*, number of samples; % > PEL, % of samples greater than permissible exposure limit; % > REL, % of samples greater than recommended exposure limit.

[a] This variable is identified as "job_cd_desc" in the *Personal Health Samples* dataset.

[b] Represents occupations associated with drilling and production operations (not all occupations shown).

laboratories (39.3 µg/m^3), milling activities that occur in shops (48.6 µg/m^3), and grinding (38.2 µg/m^3). The exceedance fractions for the NIOSH REL remain high, particularly in bagging (42.3%), dry screening (35.8%), and crushing (32.1%), all of which occur in mills.

4 | DISCUSSION

During 2000–2019, 11.8% of 55,265 personal respirable dust samples were collected by MSHA and found to have had >1% quartz exceeded the PEL. MSHA's respirable dust sampling data (contaminant 523) were used as an indicator of the likelihood of overexposure to RCS. The results indicated the need for improved control of silica exposures in M/NM mines. Among all M/NM miners sampled by MSHA health inspectors in 2000–2019, 27.3% had personal exposures that exceeded the NIOSH REL, 50 µg/m^3. The overall AM exposure for the 20-year period (47.8 µg/m^3) was very close to the NIOSH REL, indicating prevalent silica hazards in the M/NM mines inspected. However, when all samples were grouped into 5-year intervals, the AMs differed significantly, with 2010–2014 having the lowest average exposures (43.0 µg/m^3) compared to year ranges 2005–2009 (51.1 µg/m^3) and 2015–2019 (51.2 µg/m^3). The same fluctuations across the 5-year intervals were observed for the REL exceedance fractions.

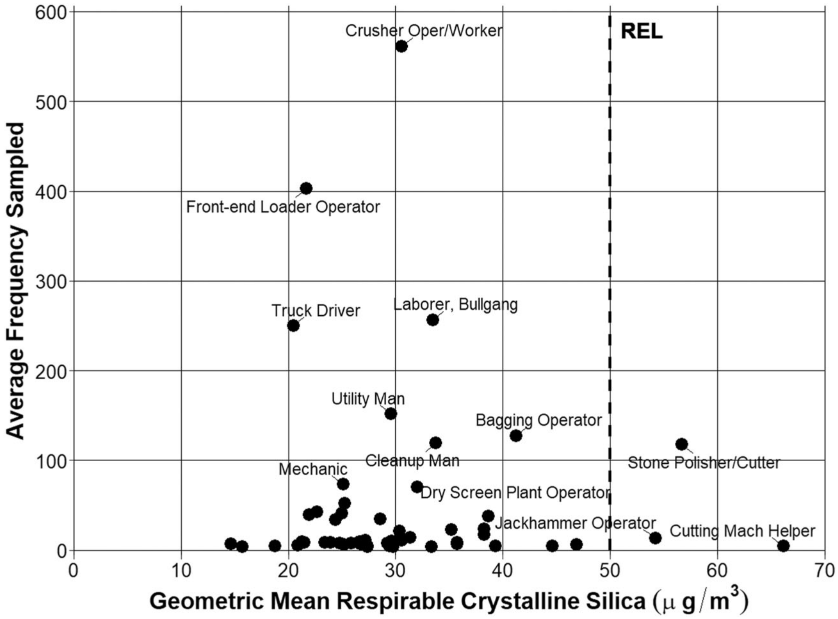

FIGURE 4 Average annual frequency of sampling versus overall geometric mean exposure by occupation, among occupations with >50 samples ($n = 53$) in metal and nonmetal mines. Mine Safety and Health Administration, 2000–2019. REL, recommended exposure limit.

TABLE 4 Respirable crystalline silica exposures by mine location[a] (n>1000) among metal and nonmetal mines, MSHA, 2000–2019

Mine location[b]	*N*	% > PEL	% > REL	GM % Silica	AM (μg/m^3)	95th (μg/m^3)	GM (μg/m^3)	GSD	95% CL of GM lower limit (μg/m^3)	95% CL of GM upper limit (μg/m^3)
s—Active production	13,352	10.2	25.1	8.6	45.0	140.2	27.7	2.5	27.3	28.2
S—Ore processing	8524	13.1	31.0	8.4	51.2	158.5	31.4	2.5	30.7	32.0
M—Crushing	6149	14.2	32.1	8.5	53.8	165.4	32.7	2.6	31.9	33.5
S—Load-in/out, stockpiles	4669	6.4	17.5	7.4	33.9	96.3	22.3	2.3	21.7	22.8
S—General	4634	10.8	25.4	8.3	46.5	146.0	28.1	2.5	27.4	28.9
M—General	3673	12.3	28.2	7.3	49.8	158.5	29.3	2.6	28.4	30.2
M—Bagging	2494	21.4	42.3	7.5	65.4	200.2	40.7	2.6	39.2	42.2
M—Load-in/out, stockpiles	2308	8.9	23.0	7.6	39.0	117.2	25.2	2.4	24.3	26.1
M—Dry screening	1390	17.6	35.8	9.0	65.1	193.3	35.9	2.7	34.0	37.8
UG—Active production	1362	16.6	27.8	4.4	51.5	160.4	29.5	2.6	28.0	31.0
S—Roads	1153	3.9	11.5	6.3	27.7	78.8	19.4	2.2	18.5	20.3
M—Washing & screening	1133	4.8	14.0	8.3	30.7	83.7	21.4	2.2	20.5	22.4

Abbreviations: 95th, 95th percentile; AM, arithmetic mean; CL, confidence limit; GM, geometric mean; GSD, geometric standard deviation; M, mills; MSHA, Mine Safety and Health Administration; *N*, number of samples; S, surface; UG, underground; % > PEL, % of samples greater than permissible exposure limit; % > REL, % of samples greater than recommended exposure limit.

[a] This variable is identified as “location_cd_desc” in the *Personal Health Samples* dataset.

[b] Samples labeled “S—,” “UG—,” and “M—” do not necessarily correspond to the associated current mine type.

Our findings are similar to findings in previous studies using MSHA's M/NM compliance data for respirable dust samples with >1% quartz (crystalline silica) in Weeks and Rose[20] and a follow-up study by Watts et al.[21] For 1998–2002, Weeks and Rose[20] found 11.5% of the samples exceeded the PEL, and 27.2% exceeded the REL. Watts et al.[21] found that between 1974 and 1980 and between 1989 and 2010, there were slight downward trends by year for the GM exposures (μg/m^3) for surface mines and mills only. However, both studies and our current work found fluctuations in GM exposures over time. Possible influences on the annual GM exposures we report may include but are not limited to, changes in MSHA's sampling strategy, laboratory analytical methods for silica-containing dust, mining work practices, production rates, processes and engineering controls, and the number and type of active mines (by subsector) across the twenty years.

Our study found both metal mines (AM: 62.6 μg/m^3, GM: 36.8 μg/m^3) and nonmetal mines (AM: 61.9 μg/m^3, GM: 36.2 μg/m^3) had higher average exposures compared to both stone mines and sand and gravel mines, which are more numerous, frequently sampled by MSHA, and primarily surface operations. Over the 20 years, the most sampled commodities (e.g., construction sand and gravel; crushed, broken limestone (NEC); crushed, broken stone (NEC); and crushed, broken granite) are consistent with the respective number of active mines for each over the period. Colinet and Thimons[25] reported that sand plants, dimension stone shops, and underground limestone mines remain challenging for ventilation and have a high potential for dust exposure.

We examined sampling frequency and found that during the 20-year period in our study individual M/NM mines were sampled infrequently for RCS (quartz), with a median of three samples per mine over the 20 years observed. The frequency of samples per mine ranged widely, from 1 to 137 samples, but only nine mines had greater than 100 respirable silica samples recorded. Given that sampling intentionally targets areas of potential high exposure and exceedance (based on targeting "high risk" occupations), and a violation and citation will immediately trigger a resampling of the same occupation at a subsequent time, it is likely that certain mines and occupations would be sampled more than others. Additionally, there are some mines that could have become inactive after being sampled. Among 53 occupations with at least 50 samples collected over 20 years, we found that the average sampling frequency per year was highly variable by occupation (3–561 samples/year), and overall, there was no association between the annual average sampling frequency and the mean intensity of silica exposures, as indicated by the GMs.

MSHA is mandated to inspect mines four times per year at active underground mines and two times per year at active surface mines. The inspection can be either a safety or a health inspection, or a comprehensive inspection for both. Health inspections can be for any regulated substance, not necessarily for silica. The current analysis also indicates that both the number of mines sampled for contaminant code 523 ("Quartz, respirable, >1% Qtz") and the number those samples per year decreased markedly in 2018 and 2019, while the exceedance fractions for the PEL and REL significantly increased in those years. The pattern we observed for 2018 and 2019 may be indicative of a more focused strategy to identify and sample maximum-risk workers. MSHA's health inspection sampling strategy is intended to identify (using professional judgment) maximum-risk workers and to measure the employer's compliance with the respective PEL. Moreover, inspectors may observe the mine for other hazards on the same inspection, which may result in fewer respirable dust samples per visit. Changes in mining practices, such as increased automation technology, for certain high-risk occupations, may have impacted MSHA's frequency of sampling by job or occupation type.

4.1 | Occupation

Occupations that involve cutting or breaking rock (e.g., mill, production, and drilling workers) significantly exceeded the PEL and had the highest average exposures, consistent with previous studies indicating that surface mining remains at high risk for silica-related diseases,[20,21] despite certain mandatory drilling and abrasive blasting dust controls for metal and nonmetal mines.[37] One possible reason may be working for several hours in very dusty working conditions, potentially without consistently using adequate control technologies (ventilation and environmental cabs). Halldin et al.[26] reported that miners may not always receive substantial respiratory protection training on the hazards of dust. Haas et al.[38] found bagger operators were aware that their primary health concern at their worksite was silica dust exposure, and seeing dust circulate in the air served as a reminder for workers to wear respirators, even if it was not required in a certain area. Though these attitudes relaxed with the length of mining tenure, moderately tenured miners perceived less susceptibility as compared to new miners and miners nearing retirement.[38] This evidence suggests ongoing annual refresher training required for miners provides an opportunity to reemphasize the risks of RCS overexposure and improved hazard recognition and behavioral interventions for both mine operators and workers.

We found occupations associated with drilling and production operations had several of the highest RCS exposures. Bagging operators in mills and ore processing areas, and other production occupations (e.g., cutters, polishers, utility men, dry sand fillers, and laborers/bullgang) which involve grinding, cutting, and packing of materials are more frequently found to have exposures exceeding the PEL than other occupations. Mine workers in bagging operations are particularly notable with nearly half (42.5%) of all samples exceeding the REL, and average exposure levels showed no downward trend and have been widely considered one of the maximum-risk occupations requiring significant dust controls.[9,39] Higher exceedances and average exposures were also observed among occupations like kiln/dryer operator, ball mill operator, bobcat operator, and jackhammer operator, consistent with results reported by Watts et al.[21] We also observed high exposure levels in an unexpected mine location—the laboratories. Occupations like lab technician or dust sampler are not normally occupations cited in the literature as high-risk. The high exposure values for laboratory workers were limited to specific years (2006, 2011, 2015, 2017, and 2018), unlike tasks in mills which consistently had higher exposures. The high lab exposures were likely due to specific tasks (e.g., handling silica-laden ore or indirect exposure from other activities), indicating that all areas of the mine, including the laboratories that process ore, should be considered for the exposure assessments instead of relying solely on prior knowledge of high-exposure occupations.

Crusher operators are among the most common occupations found at M/NM mines as well as being one of the occupations with the greatest potential risk of silica overexposure. Watts et al.[21] observed a downward trend and improvement in exposure levels for crusher operators from 1993 to 2010. In our study of personal samples with >1% quartz, we observed that from 2000 to 2017, average exposures remained between 41.3 and 54.4 μg/m^3, with a significant uptick to 75.5 μg/m^3 in 2018. Despite being the most frequently sampled occupation in the dataset, the number of crusher operator samples significantly declined in the last decade of the study period. One possible reason is that crusher operators had an improvement in dust exposure levels due to the ability to integrate controls such as enclosed cabs and booths and improved air conditioning and filtration, compared to those occupations that involve mobile equipment which requires workers to move around processing operations.[9] Similar findings were observed for other widely sampled occupations including truck drivers and front-end loader operators.

4.2 | Interpreting measured exposures

In coal mining, acute and regular silicosis cases have been identified in surface mine (blast hole) drillers who drill through siliceous rock,[26] and many severe and rapidly progressing pneumoconiosis cases have been identified in Appalachian silica-exposed underground roof bolters and thin-seam miners, and surface (blast hole) drillers[40,41] for decades. Based on the long-term prevalence of high exposures in the M/NM mining population we would expect to see similar reports of silica-related disease cases, but unlike coal miners, M/NM miners do not have the benefit of federally mandated health surveillance programs.

Given the high variability in exposures observed, a single sample for a worker should not be considered representative of that worker's cumulative exposure. This study and its predecessors show the value of analyzing aggregated data by occupation, mine type, and location. Across occupations and mine locations, variability may be due to differences in engineering controls, work practices, production rates, and environmental conditions. Despite improvements in engineering controls, they can become damaged, deteriorate, or not function properly on any given day. To that end, the importance of frequent monitoring using noncompliance tools such as the rapid quartz monitors (also known as “end-of-shift” monitors)[42] and voluntary noncompliance respirable dust monitoring by the mine operator, reinforces the importance of relying on multiple approaches to reducing exposures. Ongoing observations, sampling and enforcement are critical to ensure that workers remain safe from overexposure.

Our results point to a continuing need for further reduction of worker exposures among several occupations in M/NM mining for the prevention of respiratory illnesses, like silicosis. Continuing to evaluate these data over time can improve conditions and protections for mine workers. The methods should be replicated at the mine operator level to identify the highest risk occupations and focused interventions. Hazard surveillance is useful when a clear exposure-outcome relationship has been established, as is the case for silica and silicosis. These data have utility for hazard surveillance over time, given that hazardous silica exposures are a leading indicator for chronic diseases. Both occupation and location-based exposure data presented in this analysis can be useful at the mine operator level to more specifically identify occupations and areas that can benefit from additional monitoring and interventions, such as engineering controls. Having aggregate data with many samples for silica allows for the examination of variability by different exposure factors, including occupation, location in the mine, and industry subsector. While some mining operations may have a limited number of occupations, showing the distribution of exposures across different potentially contributing factors highlights areas or occupations with potentially more risk of overexposure. This information can help mine operators allocate resources used for exposure monitoring and exposure controls more effectively.

Obtaining serial (multiple, over time) exposure measurements for individual workers provides an opportunity to observe temporal patterns in the worker's exposure, between-worker exposure variability, an indicator of variable work practices, and better estimation of workers' cumulative exposure risk. For example, utilizing dust assessment tools such as the NIOSH-developed Helmet-Cam respirable dust exposure assessment technology, in which mine workers are instructed to wear a real-time aerosol monitor (in a backpack, safety belt, or safety vest) and a video recorder on their hardhat, can help mine operators analyze dust exposure data in a timely and more detailed manner to better identify the specific tasks, processes and work areas with elevated exposures.[43,44] It is understood that at some sites workers may perform multiple tasks within (or outside of) their primary job description. For work settings where miners perform a series of disparate tasks each shift, it is important to determine the specific tasks and length of time workers conduct each task to establish relevant task-based control strategies. The benefit of conducting serial sampling is not only to identify persistent exposures, but also to maintain long-term health, thus reducing absenteeism and presenteeism, and raise miner awareness regarding best practices, and providing a positive message to workers that their health and well-being are prioritized.

5 | LIMITATIONS

We used databases MSHA designed for administration and targeted enforcement of regulatory standards, not for research. The limitations of MSHA exposure data have been described previously.[19-21] Specific to this study, sites and workers selected for silica sampling were not necessarily representative of all workers in the M/NM subsector. Due to the nonrandom sampling strategy and potential lack of independence between observations, results are not generalizable to all mines or mine workers. Furthermore, as the data analyzed for this study are restricted to personal samples with over 1% RCS concentration, these results should not be assumed or used to characterize all respirable dust exposures in mines, settings, or job titles sampled by MSHA inspectors. Given that these data were not collected using probabilistic (statistical) sampling, samples may not be independent, and the traditional statistical assumptions of randomness are not met by these data. Personal air sampling times were not available, and TWAs for the actual sampling periods could not be used.

6 | CONCLUSION

Research on mining safety and health in the United States plays an important part in protecting the lives of mine workers. The results of this study show that exposures above the MSHA PEL for respirable dust with ≥1% quartz and the NIOSH REL for RCS (silica) continue to occur in both underground and surface M/NM mines across multiple industry subsectors, mine locations, and occupations, and they inform our understanding of the patterns of hazardous exposures. Fortunately, the exposure distributions also demonstrate that reducing overexposure to respirable silica dust is possible. Our methods and findings highlight several occupations (e.g., stone polisher/cutter, bagging operator, and cleanup man) and mine locations (e.g., activities occurring in mills) that might benefit from additional mine-specific engineering exposure controls at current or future mining operations within all metal and nonmetal sectors.

AUTHOR CONTRIBUTIONS

Shilpi Misra acquired and analyzed the data and prepared findings with considerable support interpreting the results and drafting the manuscript from Aaron L. Sussell and Gerald S. Poplin. Samantha E. Wilson prepared the graphics and did analyses in collaboration with Shilpi Misra and Aaron L. Sussell.

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CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

DISCLOSURE BY AJIM EDITOR OF RECORD

John Meyer declares that he has no conflict of interest in the review and publication decision regarding this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in MSHA Open Government Initiative Portal at https://arlweb.msha.gov/OpenGovernmentData/OGIMSHA.asp#msha-datasets. These data were derived from the following resources available in the public domain: Mine Safety and Health Administration (MSHA), https://arlweb.msha.gov/OpenGovernmentData/OGIMSHA.asp#msha-datasets

ETHICS APPROVAL AND INFORMED CONSENT

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DISCLAIMER

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC) or the Association of Schools and Programs of Public Health (ASPPH). Mention of any company or product does not constitute endorsement by NIOSH, CDC or the ASPPH.

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