American Journal of Industrial Medicine

WILEY

AMERICAN JOURNAL OF INDUSTRIAL MEDICINE

RESEARCH ARTICLE

Work Practices and Respirable Crystalline Silica Exposures in Stone Countertop Fabrication Shops

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Received: 21 May 2025 | **Revised:** 21 July 2025 | **Accepted:** 21 August 2025

Funding: This study was supported in part by a contract with the NSI and ISFA.

Keywords: artificial stone | engineered stone | natural stone | silica | silicosis | stone fabrication

ABSTRACT

Background: Reports of silicosis among US workers who fabricate and install stone countertops are increasing. Our aim was to better characterize work processes, stone type, occupational health practices, and exposures to respirable crystalline silica (RCS) in this industry.

Methods: A survey was administered to stone countertop fabrication shops to assess shop characteristics, controls, and operations. Shops were asked to share past RCS air monitoring reports. We examined associations between RCS concentrations and stone type, similar exposure groups (SEG), and engineering controls in multivariate models, and RCS exposures by shop.

Results: Of 257 shops surveyed, 98% reported processing both natural and engineered stone (ES), utilizing semi-automated equipment and small hand tools, and a variety of control methods. Only 42% of shops that required the use of a respirator reported conducting respirator fit testing, and only 19.5% performed medical surveillance. A total of 47% of shops reported RCS air sampling, with 38% submitting 292 RCS air samples used for this analysis. Overall, the RCS geometric mean (GM) was 14.1 $\mu g/m^3$, with 75.7% of RCS samples below the US Occupational Safety and Health Administration (OSHA) action limit (AL). However, RCS levels were highly variable (range 2.8–5100.0 $\mu g/m^3$), with 9.2% of RCS samples exceeding the OSHA permissible exposure limit (PEL), and 43.5% shops 1 or more samples above the OSHA AL. Use of small hand tools with no controls produced the highest RCS exposures, and dry work had significantly higher RCS exposures than any control method.

Conclusions: The findings underscore the extensive use of ES and the opportunity for overexposure to RCS in this industry. They highlight the need to eliminate dry processing methods, enhance respiratory protection, and perform repeated RCS sampling to monitor the effectiveness of controls. Additionally, more widespread medical surveillance is urgently needed to assess the extent of silicosis in this industry.

1 | Introduction

Engineered stone (ES), also known as artificial stone (AS), is a mixture of crushed quartz with resin binding agents, color pigments, and other additives such as glass or other stones [1, 2]. ES can contain crystalline silica in excess of 90% by weight, and its demand and popularity have grown significantly over the past two decades, becoming the most commonly used countertop material in the United States [3]. Outbreaks of silicosis in several states, primarily California, as well as multiple other countries,

Abbreviations: AL, action level; ES, engineered stone; OSHA, Occupational Safety and Health Administration; PEL, permissible exposure limit; RCS, respirable crystalline silica; RD, respirable dust; TWA, time-weighted average.

including Israel, Australia, Spain, Italy, and China, have brought attention to the substantial risks of respirable crystalline silica (RCS) exposure to workers in the ES countertop industry [4–13]. These reports have been notable for the severity of disease, relatively young age of the workers, and high prevalence of silicosis among ES workers, raising substantial concerns regarding the levels of RCS exposures, work practices, and controls in this industry [4, 5, 9, 12, 14, 15].

The processing of stone countertops typically involves several steps including cutting, grinding, and polishing the stone material with both hand-held and automated equipment and varying forms of exposure controls. As these tasks are done to meet local specifications of kitchens and bathrooms, the work is typically performed in small fabrication facilities near customers. Studies, primarily from stone fabrication facilities outside the United States and in California and Texas, have reported markedly elevated RCS exposure levels among workers who process ES products, including RCS levels above regulatory standards despite the use of recommended engineering controls [16–22]. The persistence of elevated RCS exposure levels, despite new policies to reduce exposures, led Australia to ban the importation and use of ES products as of July 2025 [23, 24]. Studies assessing workplace RCS exposures in the United States have involved relatively small numbers of stone fabrication workplaces, typically in areas where cases of ES silicosis have been reported, and with variable information on the type of equipment, engineering controls employed, and type of stone processed [16, 20, 22].

Information on workplace health and safety practices in the stone countertop industry, such as monitoring for RCS, silica medical surveillance, and respirator use and fit testing, is also limited, especially in the United States. Surasi et al. reported inadequate compliance with the OSHA silica standard by countertop shop employers in California, and an OSHA-administered questionnaire survey of ES workers in California found that only 20% workers reported respirator fit testing and only 5% reported having a silica medical examination [16, 25]. Data on such practices across the United States are needed to help target preventive interventions.

In the United States, there were an estimated 8694 stone fabrication establishments and nearly 100,000 workers were employed by them as of 2018 [8]. Whether ES can be safely fabricated is a growing concern [26–30]. The Natural Stone Institute (NSI) and International Surface Fabricators Association (ISFA) are trade organizations with approximately 1100 fabricator members across the United States and Canada. Many of these members are businesses that process countertops from both ES and natural stone. The aim of this study was to better characterize health and safety practices, work processes, and RCS exposures in a representative group of stone countertop fabrication shops using data obtained from NSI and ISFA members.

2 | Methods

2.1 | Data Sources

An online survey was developed using the Qualtrics platform and distributed by NSI and ISFA to their approximately 1100 fabricator member companies. The survey solicited information from each company regarding the number of employees, primary business areas (i.e., countertop fabrication, installation, dimensional stone [non-countertop fabrication], quarrying), types of stone processed, equipment and work practices, engineering controls, respiratory protection policies, whether they had conducted RCS air sampling or medical surveillance, and perceived needs for assistance with regulatory compliance. The Qualtrics survey was typically completed by the shop owner or manager; no information on individual employees was obtained. Survey responses and sampling reports were collected between March and May 2024.

Companies that reported conducting RCS air sampling between 2016 (when OSHA reduced the RCS PEL to $50\,\mu g/m^3$) [31] and May 2024 were asked to submit copies of their air sampling results. In cases where submitted sampling reports were incomplete (e.g., missing type(s) of stone processed), survey information from the shop was used to supplement the sampling report. Only companies that performed countertop fabrication were included in this analysis.

Workplace sampling was conducted by a range of entities, including industrial hygiene and other environmental health and safety consultants, insurance company representatives, federal OSHA, state OSHA, and, for a very limited number of establishments, company employees. The quality of the RCS reports and the extent of supporting information provided (e.g., description of shop, work tasks, specific stone types processed, recommendations for improvement) were highly variable and usually limited. Shop identifying information was removed from survey responses and sampling reports and replaced with unique codes; no personal individual-level data was obtained. This study did not meet the criteria for human subjects research and was exempt from Yale Institutional Review Board review.

Sample results for both respirable dust (RD) and RCS concentrations were evaluated as 8-h TWAs. Samples collected for less than 8 h were converted to 8-h TWAs if sampling times were provided, presuming zero exposure for non-sampled time (~ same value if sampled for $\pm$ 480 min), unless otherwise noted in the reports. For the subset of results that did not provide sampling times but the sample air volumes were provided, the air volumes were considered "Estimated Long Duration Samples" if the volumes were close to those associated with full-shift samples for their respective sampling method (i.e., ~800 L for OSHA Method ID-142, ~1000–1200 L for NIOSH Method 7500) and then considered ≅ 8-h TWA presuming $\pm$ 480 min of sampling. Sample results (21% RCS and 17% RD samples) reported as below the limits of detection (LOD) were substituted with concentration values derived from the censoring formula LOD/√2, considered appropriate for low levels (< 25%) of censoring [32].

Sample results were excluded from analysis if they met one or more of the following exclusion criteria: no results provided, problems reported during sampling (e.g., pump failure), simulated work only, short sampling durations (less than 2 h) with no information on whether the work was representative of the workday, inability to calculate an 8-h TWA for RCS due to insufficient information, or uninterpretable or inexplicable results (i.e., RCS > RD).

2.2 | Similar Exposure Groups (SEGs)/ Engineering Controls

The RCS sampling results were organized into similar exposure groups (SEGs) based upon sample type and activity, and further refined by the engineering controls employed. Most reports clearly designated personal versus area samples, but if the sample type was not specified, a category of "Not Given" was assigned. In consultation with stone countertop fabrication experts, the work activities reported were categorized into five SEGs: Small Tools, Large Tools, Installation, Material Handling, and Support. If the work activity was missing, that sample was assigned the activity of "Not Given."

Engineering control information was categorized as Dry (i.e., uncontrolled), Wet, Local Exhaust Ventilation, Wet Plus Wall Exhaust, and "Not Given" using descriptive information from the sampling reports. When specified, stone types processed during sampling were categorized as Natural Stone, Engineered Stone, Mixture of Natural and Engineered Stone, and "Not Given" if the stone type was missing. The natural stone category could include non-siliceous stone such as marble, as well as siliceous stones such as granite, quartzite, and sandstone.

2.3 | Data Analysis

Survey response data were compiled with categorical variables reported as frequencies and percentages, and continuous variables reported as means and standard deviations (SD). To assess whether the subset of shops that provided RCS monitoring data included for analysis was representative of the larger population of survey-responding shops, responses were compared using the *t*-test for continuous variables and Chi-squared or Fisher's exact test for categorical variables.

RCS and RD sample results reported below their LOD were replaced with concentration values derived from the censoring formula noted above. Air monitoring sample results were summarized for 8-h TWA RCS and RD using the descriptive statistics of sample sizes, minimum and maximum values, arithmetic means, and geometric means (GM) and geometric standard deviations (GSD). We compared RCS 8-h time-weighted averages (TWA-8 h) to the OSHA permissible exposure limit (PEL) of $50\,\mu g/m^3$ and action level (AL) of $25\,\mu g/m^3$. Frequency plots were generated for RCS by all results, and by sample type, SEG, and control. The distribution of RCS was positively skewed, so the data were log transformed and generalized linear models were used to examine associations between 8-h TWA RCS and SEG, control, and stone type separately in bivariate models. For stability of estimates, cell sizes smaller than 3 observations were excluded from these analyses. A multivariate model examining adjusted associations between RCS and SEG, control, and stone type was restricted to the Large Tools and Small Tools SEGs as these were the only SEGs for which sample results were available with different controls in place. Adequate RCS sample results were available to examine whether RCS levels differed for wet compared to dry methods within the Small Tools SEG.

Statistical analyses were performed with SAS 9.4 (SAS Institute, Cary, NC, USA) with a statistical significance level set at $p < 0.05$. Graphs were generated with Microsoft Excel version 16.86 (Microsoft Corporation, 2024) and JMP Pro 17.2.0 (SAS Institute Inc., Cary, NC).

3 | Results Shop Questionnaire

Table 1 summarizes the countertop fabrication shop characteristics and practices for all shops that completed the online survey and for the subset of shops from which RCS sampling data was analyzed. Overall, 257 unique countertop fabrication shops representing 45 states (253 shops) and Canada (4 shops) completed the online survey. The number of employees ranged from 1 to 125 per shop, with a median of 10 employees. Nearly all shops (97.7%) reported processing a mix of natural and ES, with mean fractions of about 37% natural stone and 52% ES.

Regarding the type of equipment used, 87.2% of shops reported having computer numerical control (CNC) or other semi-automated equipment. However, only 59.1% of shops reported performing nearly all cutting/shaping/drilling operations with the semi-automated equipment. Use of small hand tools was common: 34% of shops reporting cutting with hand saws, 59.5% reported hand grinding/shaping/drilling, and almost all shops (93.8%) reported hand polishing. A range of engineering controls was reported, most commonly as all wet fabrication methods (89.1%) and water-fed tools (86.4%). Less commonly reported controls were local exhaust ventilation (30.0%), enclosed CNC equipment (23.3%), submerged cutting (25.3%), and HEPA filtered air circulators (17.9%). 42% of shops reported that they had ever had an OSHA inspection, although the timing and purpose of the inspections were not explored. Fewer than half (46.7%) of shops reported conducting RCS sampling.

Shop-reported respiratory protection practices and implementation of pre-placement and medical surveillance examinations are summarized in Table 2. Of the 257 responsive shops, only 18.3% reported conducting pre-placement examinations. The reported components of these evaluations included a mix of health questionnaire (70%), spirometry (63.8%), chest X-ray (57.4%), drug testing (46.8%), and audiometry (40.4%). A similar number of shops (19.5%) reported periodic medical surveillance examinations, with a similar mix of components.

Of note, 37% of the 257 shops did not require the use of respirators, about half of which (53.7%) noted that they had tested below the OSHA PEL. Over half the shops (63%) reported requiring respiratory protection. However, only 42% of these shops reported performing fit testing, and 54% reported having a written respiratory protection program. Thus, despite recent increased attention regarding the hazards of RCS exposure in this industry and OSHA silica regulations, real-world practices regarding sampling for RCS, medical surveillance, and respiratory protection were highly variable and frequently not in compliance with the OSHA silica standard. Consistent with this finding, over 1/3 of shops surveyed noted that they wanted assistance with OSHA compliance (45.1%), medical surveillance (36.6%), RCS air monitoring (43.6%), and respiratory protection (38.5%).

TABLE 1 | Countertop fabrication shops: operation characteristics.

		Shops that completed online survey	Shops with sampling results used	*p* value
Number of shops		257	46	
Number of States represented		45	24	
Number of employees				0.002
Mean (SD)		17.2 (18.9)	28.5 (27.8)	
Median		10	20.0	
Types of employees	*n* (%)			0.0103
Independent contractors, subcontractors		93 (36.2%)	24 (52.2)	
Temporary workers		21 (8.2%)	0 (0.0)	
Employees only		143 (55.6%)	22 (47.8)	
Shop operations	*n* (%)			
Large Tools				
CNC or other semi-automated equipment		224 (87.2)	43 (93.5)	0.060
CNC cutting,shaping,drilling		208 (80.9)	41 (89.1)	0.118
Bridge Saw Cutting		198 (77.0)	38 (82.6)	0.322
Machine Polishing		208 (80.9)	43 (93.5)	0.017
Small Tools				
Cutting with hand saws		88 (34.2)	11 (23.9)	0.103
Hand grinding,shaping,drilling		153 (59.5)	22 (47.8)	0.074
Hand Polishing (air or electric)		241 (93.8)	43 (93.5)	0.927
Edge laminating,miter preparation		215 (83.6)	38 (82.6)	0.832
Cutting, shaping, drilling operations performed by a CNC or other semi-automated machine?				
Nearly all		152 (59.1)	38 (82.6)	0.0004
About 25%–75%		54 (21.0)	4 (8.7)	0.024
Not Answered		51 (19.8)	4 (8.7)	
Engineering Controls	*n* (%)			
Local exhaust ventilation		77 (30.0)	17 (37.0)	0.253
All wet fabrication methods		229 (89.1)	46 (100.0)	0.009
Water-fed tools		222 (86.4)	39 (84.8)	0.727
Submerged cutting		65 (25.3)	28 (60.9)	0.004
CNC equipment with enclosed doors		60 (23.3)	10 (21.7)	0.776
HEPA filtered air circulators		46 (17.9)	17 (37.0)	0.0002
Specialized floor scrubbers		36 (14.0)	13 (28.3)	0.002
Stone type(s) processed	*n* (%)			
Mix of natural and engineered stone		251 (97.7%)	46 (100.0)	
Natural stone only		1 (0.3%)		
Other (acrylic solid surfaces, mixes)		5 (1.9%)		
If Mix, what fraction of stone processed in shop				
Natural stone	Mean (SD)	37.1% (18.9)	33.3 (18.8)	0.132
Engineered stone	Mean (SD)	52% (19.3)	49.0 (21.2)	0.243
Have had an OSHA inspection?	Yes	109 (42.4%)	23 (50.0)	0.028
Performed RCS air sampling	Yes	120 (46.7)	46 (100.0)	< 0.0001

(Continues)

TABLE 1 | (Continued)

		Shops that completed online survey	Shops with sampling results used	*p* value
Number of RCS samples	Unknown		292	
Samples per shop	Mean (SD)		6.3 (7.8)	

Abbreviations: CNC = computer numerical control, RCS = respirable crystalline silica, SD = standard deviation.

3.1 | RCS Sampling Results

Of the 120 shops that reported conducting RCS sampling, 55 shops (45.8%) provided sampling reports with varying degrees of information on 336 RCS samples, 292 (87%) of which could be used for this analysis. Forty-four (13%) samples from 9 shops were excluded based on the exclusion criteria noted earlier, most commonly from too short a duration of sampling ($n = 10$), insufficient information to calculate an 8-h TWA for RCS ($n = 14$), or sampling problems ($n = 8$), as shown in Table SI. Thus, 292 RCS sample results were used in this analysis, with 4 shops submitting results from more than 1 year. The usable RCS sample results came from 46 shops (42 shops from 24 US states and 4 shops from Canada), with a mean of 6.3 (median 4.0) samples obtained per shop (Table 1). Figure S1 shows the geographical distribution of the 42 US shops that submitted RCS sampling reports used for analysis.

The subset of 46 shops with usable RCS data was compared to all 257 shops that completed the survey, to assess the potential for shop selection bias (Tables 1 and 2). Shops from which RCS samples were analyzed had significantly more employees (median 20 vs. 10) and were significantly more likely to report use of the following: CNC or other semi-automated equipment for nearly all cutting/shaping/drilling (82.6% vs. 59.1%), submerged cutting (60.9% vs. 25.3%), all wet fabrication methods (100% vs. 89.1%), and higher rates of HEPA filtered room air circulators (37.0% vs. 17.9%) and the use of specialized floor scrubbing equipment (28.3% vs. 14.0%). These findings suggest that the subset of shops supplying RCS samples was larger and employed more engineering controls than the superset of shops that completed the survey.

As shown in Table 2, the subset of shops that provided usable RCS sampling results was also significantly more likely to report performing pre-placement (41.3% vs. 18.3%) and periodic medical surveillance (45.6% vs. 19.5%) evaluations. The frequency of performing specific components of the evaluations (e.g., chest X-ray, spirometry) was similar in the 2 groups (data not shown). Also of note, the shops that submitted RCS sampling data were significantly less likely to require respiratory protection (50.0% vs. 63.0%), but significantly more likely to perform respiratory fit testing (73.9% vs. 42%) and to have a written respiratory protection program (91.3% vs. 54.3%). For those shops that reported not requiring the use of respirators, the subset that provided usable RCS sampling results was more likely to have reported that they performed RCS sampling and tested below the OSHA AL (95.6% vs 53.7%), suggesting greater compliance with OSHA silica regulations.

The 292 RCS sample levels are shown graphically by year in Figure 1. Over 80% of the samples were collected from 2022 to 2024, with no samples collected in 2020 and 2021, likely reflecting challenges during COVID-19 pandemic. Overall, RCS levels were highly variable, ranging 1,000-fold, from less than 5 $\mu g/m^3$ to over 5000 $\mu g/m^3$. While 75.7% of RCS samples were below the OSHA AL, 9.2% were above the PEL, and another 15.1% were between the AL and PEL. No significant differences in RCS levels were found over these years.

We attempted to compare RCS levels from processing natural stone vs. ES products, as shown in Table SII. However, over 80% of the 292 RCS samples were noted to have come from either a mix of natural stone and ES or the stone type was not described in the sample report. Among the 50 RCS samples where the type of stone was noted, there was no significant difference in RCS levels between the 29 ES (GM 11.2 $\mu g/m^3$) and 21 natural stone products (GM 8.7 $\mu g/m^3$). All but one of these 50 samples were below the OSHA PEL.

Table 3 and Figure 2 show the distribution of RCS samples by sample type, SEG (type of equipment/activity), and type of engineering control. Of the 292 samples, 231 (79.1%) were personal samples, 29 (9.9%) were area samples, and 32 (11.0%) did not designate whether personal or area. Among the 231 identified personal RCS samples, 99 (42.9%) were obtained from employees noted to be using small tools (RCS GM 17.3 $\mu g/m^3$), 67 (29.0%) large tools (RCS GM 12.2 $\mu g/m^3$), 13 (5.6%) installers (RCS GM 16.7 $\mu g/m^3$), and 41 (17.7%) personal samples the SEG was not specified (RCS GM 15.5 $\mu g/m^3$).

Among the 67 RCS samples from workers operating large tools, almost all (94.0%) indicated use of wet methods, with only 4 (6%) noted to be dry or use of local exhaust ventilation, 2 of which were above the AL but none above the PEL (Table 3, Figure 2). Overall, 10 (14.9%) of the samples from workers operating large tools showed RCS levels between the AL and PEL, and 3 (4.5%) exceeded the PEL, with the highest RCS level being 118.0 $\mu g/m^3$.

Not surprisingly, the highest individual exposure measurements were among the 8 RCS samples from workers using small tools with no controls (i.e., “dry”) ($n = 6$, GM 271.4 $\mu g/m^3$) or dry with local exhaust ventilation ($n = 2$, GM 40.9 $\mu g/m^3$), with 75% of these 8 samples > PEL, as shown in Figure 2 and Table 3. Among the 80 samples obtained from workers who used small tools with wet methods, 26.3% had RCS exposures between the AL and PEL, and 6.2% had exposures > PEL. Workers operating small tools with wet methods (GM 14.9 $\mu g/m^3$, GSD 2.4) had significantly lower RCS exposures compared to those operating small tools with dry methods (GM 271.4 $\mu g/m^3$, GSD 7.9).

Of note, for the 13 RCS samples obtained from installation workers, 30.8% were above the PEL. Among the 41 personal

TABLE 2 | Countertop fabrication shops: Medical evaluations/respiratory protection.

		Shops that completed online survey, *n* (%)	Shops with sampling results used, *n* (%)	*p* value*
Number of shops		257 (100.0)	46 (100.0)	
Medical evaluations				
Provide pre-placement exams				**< 0.0001**
	Yes	47 (18.3)	19 (41.3)	
	No	210 (81.7)	27 (58.7)	
Perform medical surveillance				**< 0.0001**
	Yes	50 (19.5)	21 (45.6)	
	No	207 (80.5)	25 (54.3)	
Respiratory protection practices				
Require use of respirators for any work tasks				**0.0432**
	Yes	162 (63.0)	23 (50.0)	
	No	95 (37.0)	23 (50.0)	
Perform respirator fit testing		($n = 162$)	**($n = 23$)**	**0.004**
	Yes	68 (42.0)	17 (73.9)	
	No	92 (56.8)	6 (26.1)	
	Missing	2 (1.2)		
Have a written respiratory protection program				**0.0006**
	Yes	88 (54.3)	21 (91.3)	
	No	72 (44.4)	2 (8.7)	
	Missing	2 (1.2)	0	
Do not require use of respirators		($n = 95$)	**($n = 23$)**	
	We have tested below OSHA Action Limit	51 (53.7)	22 (95.6)	**< 0.0001**
	Respirator use is optional, provided by employer	18 (18.9)	1 (4.3)	0.0631
	We have not conducted air tests & do not require respirators	26 (27.4)	0	**0.0007**
Shops want Assistance with:				
	OSHA compliance	116 (45.1)	17 (36.7)	0.219

(Continues)

TABLE 2 | (Continued)

	Shops that completed online survey, *n* (%)	Shops with sampling results used, *n* (%)	*p* value*
Medical Surveillance	94 (36.6)	17 (37.0)	0.953
Air monitoring for RCS	112 (43.6)	20 (43.5)	0.988
Respiratory protection selection and use	99 (38.5)	15 (32.6)	0.363

Abbreviation: RCS, respirable crystalline silica.
*Chi-squared or Fisher's exact test was used to compare differences between the shops that completed the survey and shops for which RCS sampling results were used. Bold font indicates statistical significance.

RCS samples where the SEG was not provided, 6 (14.6%) were above the PEL and another 5 (12.2%) were between the AL and PEL; all but one of these were noted to have used wet methods. Other SEGs with smaller numbers of samples included material handling and support workers; none of these sample results were ≥ AL.

Results of the multivariate analysis used to adjust for differences in engineering controls, SEG, and stone type are shown in Table 4. RCS exposures using dry fabrication methods were significantly higher than any of the control methods ($p < 0.01$) (Table 4 and Figure 3). Workers operating small tools had significantly higher RCS exposure than those operating large tools ($p < 0.05$). In the multivariate model, workers fabricating ES did not have significantly different RCS exposure compared to those fabricating natural stone, a mix of ES and natural stone, or unspecified stone type, likely since most of the samples were from shops using a mixture of stone types or the stone types were not specified.

3.2 | RCS Samples by Shop

The distribution of RCS samples was also evaluated by shop (Figure 4), in descending categorical order from the shop with the highest single RCS level (5100 $\mu g/m^3$) to the shop with the lowest RCS level (2.8 $\mu g/m^3$), with the samples from each shop displayed graphically in a dot plot. For the 4 shops with repeat sampling over time (marked with arrows), RCS results from all years were combined. Of note, for the 4 highest RCS levels (all > 250 $\mu g/m^3$), all workers were reported as using hand tools without wet controls and they were from 2 shops. Of the 46 shops, 11 (23.4%) shops had at least 1 sample above the PEL, 9 shops (19.6%) had at least 1 sample between the AL and PEL, and 26 shops (56.5%) had all samples below the AL. Also of note, all shops with RCS levels above the PEL reported requiring the use of respirators, except for one that had only submitted results from 2019 and then reported testing in 2024 below the AL.

Compliance with OSHA-mandated medical surveillance was less consistent. Of the 20 shops with one or more RCS sampling results that were at or above the AL, only 10 (50%) reported performing medical surveillance. Among those shops that reported providing medical surveillance, spirometry was included in 68% and chest X-ray in 74% of medical surveillance programs, also not in compliance with OSHA-mandated medical surveillance requirements.

RCS levels from the 4 shops that submitted sampling results over multiple years (2–5) are shown in Figure 5. Unfortunately, information about any changes made to work practices or stone substrates was not available. Overall, RCS levels in these 4 shops declined over time, with the most recent sampling showing all shops below the PEL, but with 3 of the 4 shops having 1 sample above the AL. For Shop A, all RCS samples were below the AL at both time points. Shops B and D had RCS exposures above the PEL in prior years, but with their most recent sampling showing all samples below the PEL. Shop C submitted multiple RCS sampling results over 6 years (2016–2022), with all RCS exposures below the PEL, and only 1

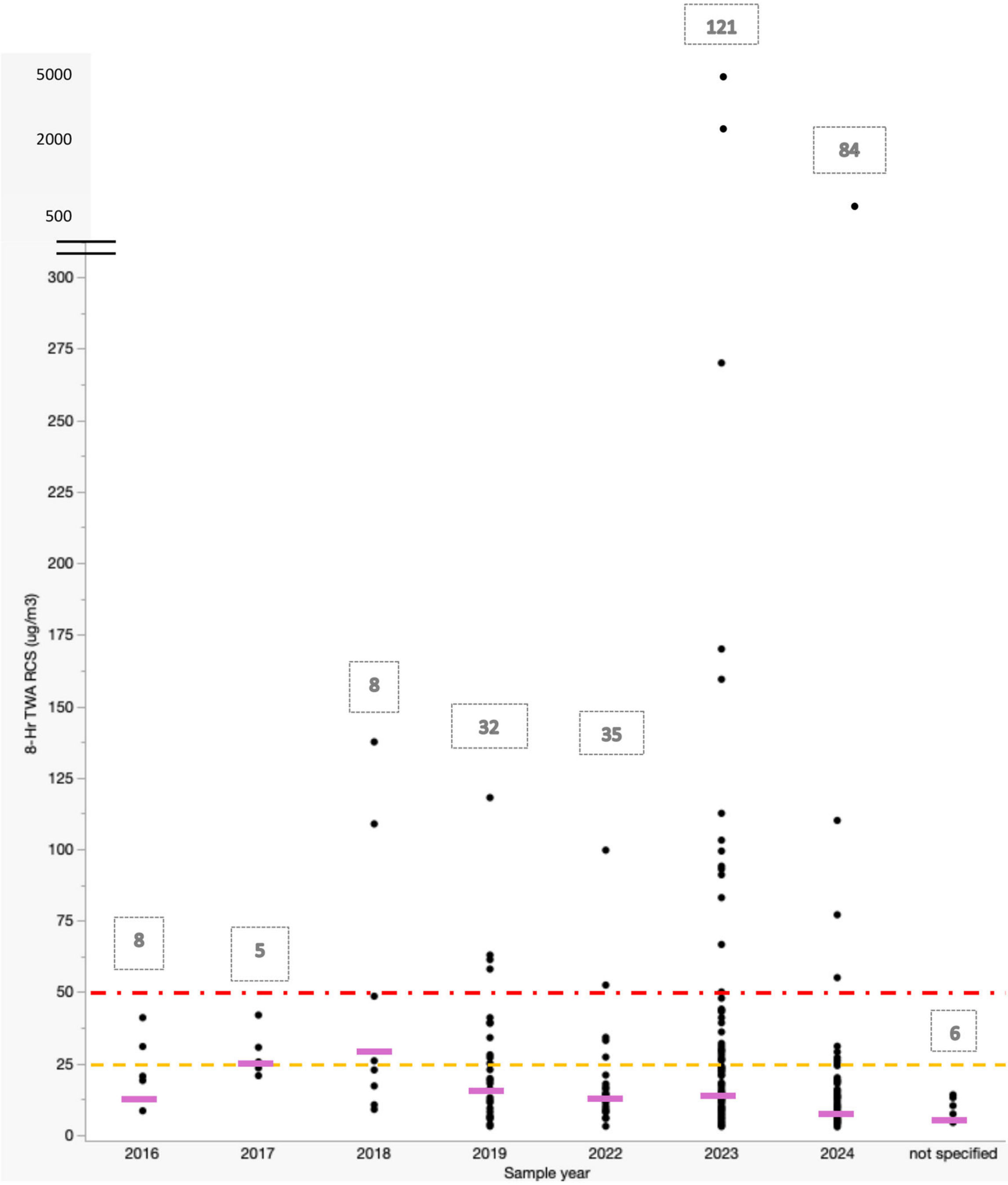

FIGURE 1 | RCS sample results by year. Submitted RCS sample results by year. shows the number of samples. indicates geometric mean, indicates PEL, indicates AL. *Note:* Samples from 2024 represented a partial year, from January to May only. AL = action limit, PEL = permissible exposure limit, RCS = respirable crystalline silica, TWA = time-weighted average. To incorporate the three highest RCS values (570, 2100, 5100 μg/m^3), a break in the y-axis from 300 to 500 μg/m^3 was necessary and depicted by the double lines.

sample since 2017 above the AL. These 4 shops demonstrate the importance of repeated sampling over time to assess the adequacy of engineering controls and work practices. They also demonstrate that combining sampling over time, as done in Figure 4, as well as obtaining more RCS samples in general, can increase the number of shops considered above the PEL, when defined as ≥ 1 sample above the PEL, without considering the total number of samples and when they were collected. The data from these 4 shops also demonstrate the value in repeated sampling over time in assessing the adequacy of controls, assuming that such sampling includes the highest risk activities, an assumption that is difficult to confirm without independent direct observation.

Respirable dust (RD) results were also available for 218 of the 292 RCS sampling results, as shown in Table SIII. Overall, RD levels ranged from 22.2 to 6800 μg/m^3, with a GM of 117.4 μg/m^3. Of note, the percent of RCS in RD varied widely from 1% to 75%, making it difficult to estimate RCS from RD levels.

TABLE 3 | Respirable crystalline silica (RCS) exposures by sample type, similar exposure group (SEG), and controls.

Sample type	SEG and type of controls		Respirable crystalline silica (μg/m^3)						
			n	**Range**	**AM**	**GM**	**< 25 μg/m^3, *n* (%)**	**≥ 25 μg/m^3 ≤ 50 μg/m^3, *n* (%)**	**> 50 μg/m^3, *n* (%)**
Personal ($n = 231$)	SEG large tools	Control							
		Dry	2	26.0–44.0	35.0	33.8	0	2 (100)	0
		LEV	2	2.9–21.0	12.0	7.9	2 (100)	0	0
		Wet	61	2.9–118.0	19.0	12.3	50 (82.0)	8 (13.1)	3 (4.9)
		Wet and wall exhaust	2	5.7–5.7	5.7	5.7	2 (100)	0	0
		Total large tools	67	2.9–118.0	18.8	12.2	54 (80.6)	10 (14.9)	3 (4.5)
	SEG small tools	Control							
		Dry	6	26.9–5100.0	1258.0	271.4	0	1 (16.7)	5 (83.3)
		Dry with LEV	2	2.9–570.0	286.5	40.9	1 (50.0)	0	1 (50.0)
		Wet	80	2.9–99.6	21.3	14.9	54 (67.5)	21 (26.3)	5 (6.2)
		Wet and wall exhaust	3	5.8–6.0	5.9	5.9	3 (100)	0	0
		Wet and dry	1	55.0			0	0	1
		Not Given	7	4.3– 33.0	12.7	9.5	6 (85.7)	1 (14.3)	0
		Total small tools	99	2.9–5100.0	100.9	17.3	64 (64.6)	23 (23.2)	12 (12.1)
	SEG	Control not given							
	Installation		13	2.9–170.0	47.8	16.7	7 (53.8)	2 (15.4)	4 (30.8)
	Material handling		7	2.8–22.0	10.7	8.4	7 (100)	0	0
	Support		4	4.4–13.7	8.4	7.7	4 (100)	0	0
	SEG not given	Control							
		LEV	1	14.0			1 (100)	0	0
		Wet	40	3.0–159.4	27.1	15.57	29 (72.5)	5 (12.5)	6 (15.0)
		Total SEG not given	41	3.0–159.4	26.8	15.5	30 (73.2)	5 (12.2)	6 (14.6)
		Total personal samples	231	2.9–5100	?	?	166 (71.9)	40 (17.3)	25 (10.8)
Not given ($n = 32$)	SEG not given	Control							
		Wet	32	3.7–62.9	16.5	13.3	29 (90.6)	1 (3.1)	2 (6.2)
Area ($n = 29$)		Shop	26	4.3–39.3	13.8	11.1	23(88.5)	3 (11.5)	0
		Non-Shop	3	4.3–13.0	7.2	6.3	3 (100)	0	0
		Total area samples	29	4.3–39.3	13.1	10.5	26 (89.7)	3 (10.3)	0
Total all samples			292	2.8–5100.0	47.9	14.1	221 (75.7)	44 (15.1)	27 (9.2)

Abbreviations: AM = arithmetic mean, GM = geometric mean, LEV = local exhaust ventilation, RCS = respirable crystalline silica, SEG = similar exposure group.

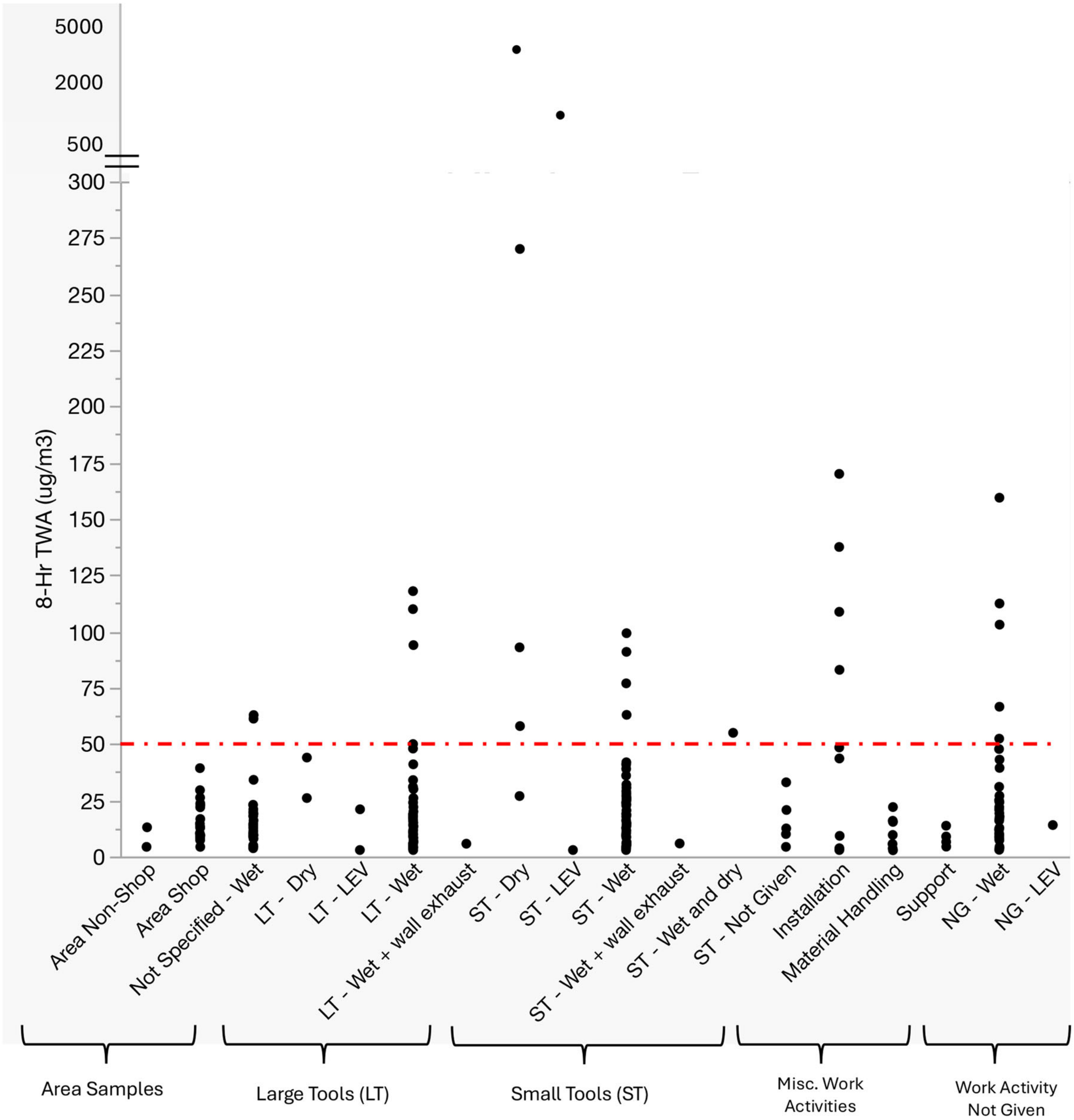

FIGURE 2 | RCS exposures by SEG and Control(s) in Use. Distribution of RCS sample results (8-h TWA in μg/m^3) grouped by sample type, SEG, and control(s) in use. LT = large tools, NG = not given, RCS = respirable crystalline silica, SEG = similar exposure group, ST = small tools, TWA = time-weighted average. ▬ · ▬ · · ▬ indicates the permissible exposure limit (PEL) of 50 μg/m^3.

4 | Discussion

This study provides important new information on work practices and controls in stone fabrication shops based upon a survey of 257 stone fabrication establishments in 45 states across the United States and Canada. The study also characterizes real-world RCS exposures among workers in this industry, based upon nearly 300 air samples obtained from 42 shops in 24 states and 4 shops in Canada.

The survey confirmed the widespread use of both ES and natural stone in countertop fabrication work in almost every shop that responded. It also confirmed the widespread use of both automated equipment and small hand tools, and that while wet methods to control dust are very common (89%), they are not universal. Only 42% reported performing respirator fit testing in shops that require the use of a respirator, and even fewer shops (19.5%) reported performing medical surveillance. These findings are generally similar to reports from California, Texas, Australia, and other countries, which have noted the persistence of dry cutting in some establishments, and also that noncompliance with medical surveillance and respiratory protection regulations is common [12, 16, 18, 25]. Also notable in our findings is that medical surveillance was frequently found to be missing key components, including chest X-rays or spirometry, suggesting that many of the occupational health professionals that member shops have contracted with do not provide appropriate and compliant medical surveillance. These survey findings highlight the need for more widespread medical surveillance and respiratory protection programs, including respirator fit testing. They also highlight the problem of inadequate silica medical surveillance, which can provide false reassurance.

TABLE 4 | Multivariate Model results RCS (ln 8-h TWA) by SEG, control, and stone type (ln 8-h TWA).

			***p* value**
Controls			< 0.0001
SEG			0.0283
Stone type			0.2940
	Estimate	Standard error	*p* value
Small tools	0.33	0.16	0.0457
Large tools (reference)	reference		
LEV	−2.10	0.68	0.0025
NG	−2.93	0.51	< 0.0001
Wet	−2.30	0.36	< 0.0001
Wet plus wall exhaust	−3.15	0.58	< 0.0001
Dry (reference)	reference		
Engineered stone	0.29	0.34	0.4109
Mix engineered and natural stone	0.52	0.28	0.0691
Not given	0.35	0.29	0.2272
Natural stone (reference)	reference		

Abbreviations: LEV = local exhaust ventilation, NG = not given, RCS = respirable crystalline silica, SEG = similar exposure group, TWA = time-weighted average.

Key findings from the RCS sampling results were the variability in RCS exposure levels across different shops, SEGs, and engineering controls, with RCS exposures ranging from 2.8 to 5100 μg/m^3, with a GM of 14.1 μg/m^3. The 4 highest RCS levels were from workers in 2 shops using small tools without wet methods. Multivariate analysis showed that dry work produced significantly higher RCS exposures than seen with any engineering control method, and also that tasks involving automated tools resulted in lower RCS exposures than those involving small hand tools. Exposures did not differ based upon stone type, although the specific types of ES and natural stone were unknown and, for the majority of samples, the stone types were mixed.

These findings are notable for the large number of RCS samples collected (almost 300) under actual work conditions from 46 shops in 24 US states and Canada, and for documenting the specific equipment, tasks, and engineering controls, where possible. The findings expand upon previously available reports of RCS exposures in this industry, which come from a limited number of states in the US, primarily California and Texas, as well as other countries [12, 16–22]. While the range of RCS exposures and percentage of samples and shops above the OSHA PEL differ by study, common findings have been the large variability in RCS exposures, and, where equipment and engineering controls have been noted, the highest RCS levels (5 or more times the OSHA PEL) have been found with dry cutting [12, 17, 20, 33]. Our findings are generally consistent with prior published reports, although the upper range of exposures was higher than most reports [16, 17, 19, 22]. Additionally, compared to published data from California OSHA inspections of ES shops [16] and Georgia's OSHA Consultation Program [20], a greater fraction of personal RCS samples in this study was below the OSHA PEL, potentially reflecting more safety-conscious or better-resourced shops. Our findings also add to the more limited real-world data on different types of equipment and controls, namely that even with automated equipment and wet controls, some personal RCS samples were above the OSHA PEL, with the maximum around 100 μg/m^3, twice the OSHA PEL [17, 19–21]

Several strengths of this study are noteworthy, including the large number of shops that participated in the survey (257) and the comparatively high rate of participation. Over 20% of shops contacted completed the survey, including shops from 45 different states and Canada, a wide representation of stone fabrication facilities. The survey data provides valuable information about current reported work practices, equipment used, engineering controls, personal protective equipment policies, and occupational health services in the countertop fabrication industry across North America. While there have been selected reports, such as of stone fabrication shops and workers in California [16, 25], we are not aware of similar data from stone fabrication shops across the US. Shops did not appear to report only "correct" answers, given activities such as dry work and not performing RCS sampling were noted. In addition, almost half the shops that reported conducting RCS sampling submitted results, a high response rate for a voluntary survey in a high-demand industry.

Another strength of the study is the inclusion of nearly 300 RCS samples submitted directly to us from 46 countertop fabrication shops across 24 states and Canada. Prior published studies from stone fabrication shops have reported results from fewer than 10 up to 152 RCS samples, with varying degrees of information on equipment, work activities, or engineering controls [16, 17, 20]. Prior studies have also focused on states where cases of ES silicosis have been identified, primarily California, Texas, and, more recently, Illinois [16, 20, 22]. The large number of RCS samples in this study provides a broad perspective on the range and variability of RCS levels, as well as the activities, equipment, and controls used in the industry. Despite some missing information on specific work tasks, tools, and controls, the large sample size enabled statistical analysis of factors associated with RCS exposures.

The survey and RCS sampling results also identify several practical, real-world opportunities to target efforts and resources to reduce RCS levels and help prevent silicosis. While 4 samples had extremely high RCS levels (> 250–5100 μg/m^3), these 4 samples came from 2 shops and were obtained from workers hand-cutting without wet controls. Another 7 (15%) shops had one or more samples from their most recent air monitoring above the PEL, indicating additional shops that urgently need to improve controls, if not already implemented. However, 75.6% of all RCS samples and 57% of the shops had RCS samples that were all below the OSHA AL. Assuming such sampling is representative of the exposures in these shops, which may not be the case, the data

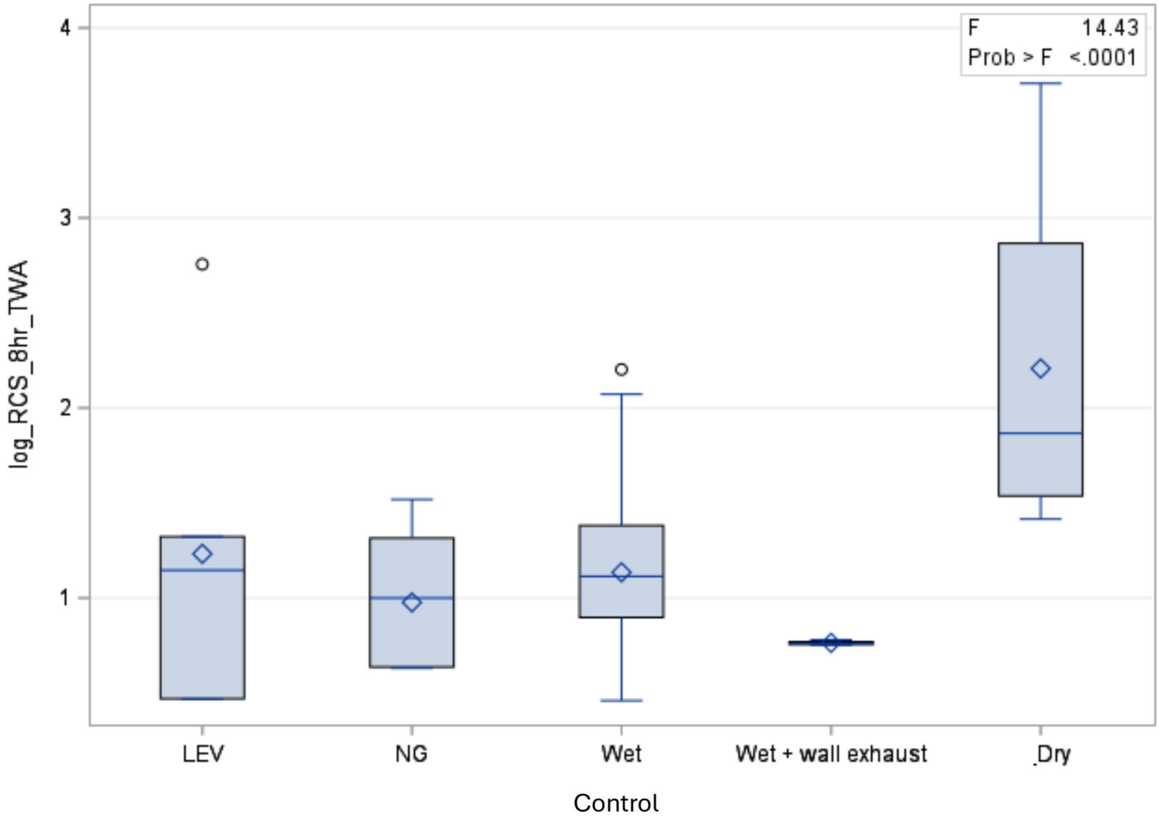

FIGURE 3 | RCS Exposure Distribution by Control (Log10 scale). Displays statistically significant difference in the distribution of RCS sample levels (8-h TWA in μg/m^3 on Log$_{10}$ scale for all control groups compared to dry work. RCS = respirable crystalline silica, TWA = time-weighted average.

indicate that some shops are able to adequately control RCS exposures. These findings are consistent with recently published findings from over 500 worksites in Australia that demonstrated that a multifaceted approach including education, inspection site visits, and regulatory changes can improve safety practices [34]. The findings also highlight the importance of repeat sampling over time to ensure that exposures remain well controlled, and that silica medical surveillance of workers in stone fabrication shops across the United States is needed to assess the efficacy of control measures and the extent of silicosis in this industry.

The survey and RCS sampling results identify specific interventions that should be prioritized, including a prohibition on all dry work, expanding the use of automated equipment to the extent possible, and implementing proper respirator and medical surveillance programs, consistent with the recommendations of others [26, 28, 30]. Areas where NSI/ISFA members identified the need for additional assistance (e.g., medical surveillance, OSHA compliance) are also consistent with the areas of concern highlighted by the data.

Despite these study strengths, we acknowledge several important study limitations, most importantly shop and sampling bias. Companies that belong to NSI and ISFA likely represent more established and more safety-conscious operations compared to all potential stone fabrication shops. Shops willing to participate in the survey, while generally representative of NSI and ISFA membership, likely represent a subgroup of more safety-conscious members. Analysis of the survey responses demonstrates that the subset of shops that submitted RCS sampling results was more likely to be compliant shops, given that they reported better engineering controls and greater compliance with OSHA's silica standard than shops that did not submit RCS samples. In addition to shop selection bias, sampling for RCS could have been performed selectively to reduce the likelihood of finding elevated RCS levels, such as on lower production work days or in areas of the shop with superior engineering controls. However, the variability in RCS levels found, including levels higher than those reported by most other studies, the large sample size across a wide geographic area, the range of individuals that performed the sampling, and the overall similar pattern of findings as other published studies help mitigate these concerns.

Although the analytical methods used were appropriate across industrial hygiene reports, another concern was that the level of detail provided was highly variable, with many samples missing key information such as the SEG, type of control(s) employed (or lack thereof), or stone type, thus resulting in a large number coded as "not given." In addition, the number of samples available for certain SEGs (e.g., installation) was limited. While these factors limited a more extensive analysis of factors such as controls and stone type, the findings nevertheless provide important information about RCS exposures across the countertop fabrication industry. While an independently funded study would enable more detailed documentation of workplace

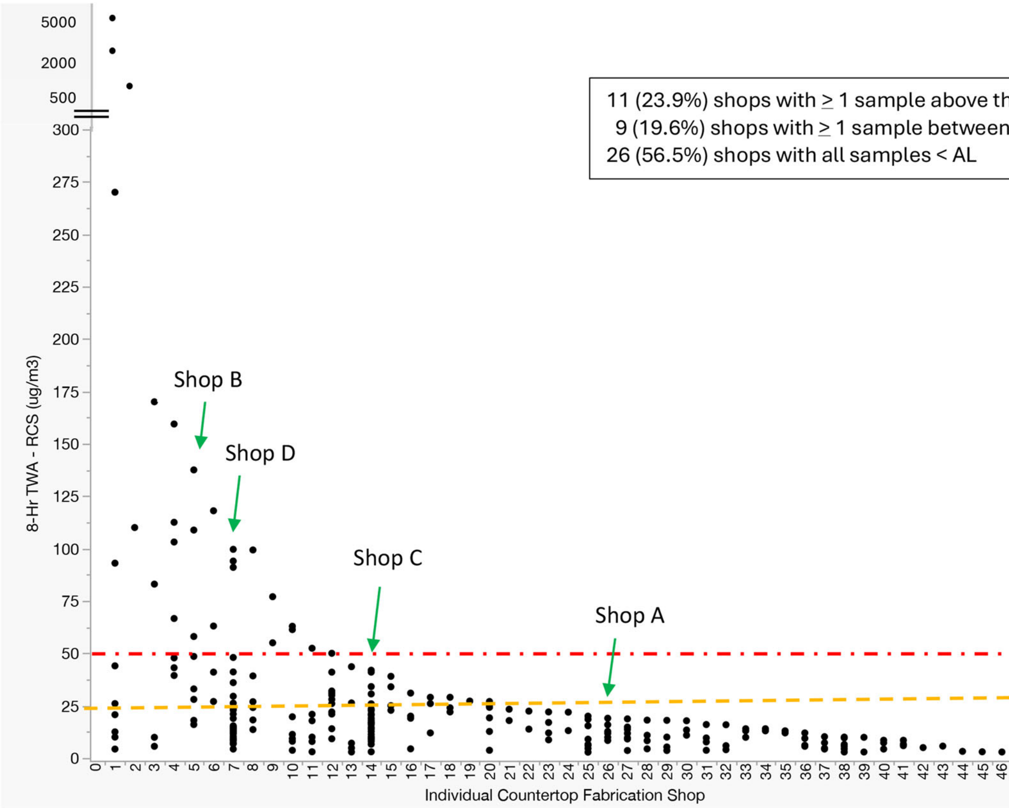

FIGURE 4 | RCS samples by shop (μg/m^3) (292 samples from 46 shops). Distribution of 292 RCS sample results (8-h TWA in μg/m^3) for each of the 46 countertop fabrication shops, grouped from shops with the highest measured RCS levels to those with the lowest levels. AL = action limit, PEL = permissible exposure limit, RCS = respirable crystalline silica, TWA = time-weighted average. indicates PEL. indicates AL. indicates RCS sample results from 4 shops with sampling over time (shops shown in Figure 5).

factors and consistent sampling and analytic methods, such a study would entail substantial funding and still require agreement by shop owners to participate, which would likely be challenging.

A related concern is that the survey data was based on self-reporting by the shop manager or owner, and thus are subject to potential bias and misinformation. For example, while the survey noted that the shops that submitted RCS samples reported using all wet methods, the sampling data indicated a small number of samples from workers dry cutting, which contradicts the self-reported survey data. Similarly, as decisions regarding the components of medical surveillance are typically made by the entity providing medical services, the information reported through the survey may not be entirely accurate. The findings of inadequate respiratory protection and medical surveillance have prompted efforts by NSI and ISFA to provide specific guidance on implementing respiratory protection and medical surveillance programs for their members.

Despite these limitations, our findings further characterize work conditions, occupational health practices, and RCS exposures in stone fabrication shops across North America. Dry cutting and use of hand tools were found to be the strongest predictors of high RCS exposures. Wet controls and local exhaust ventilation, while significantly reducing RCS exposures, did not guarantee RCS levels below the OSHA PEL.

5 | Conclusion

This study provides important real-world information on work processes, controls, respiratory protection programs, occupational health practices, and RCS levels in stone fabrication shops across the United States and Canada, based upon a survey of 257 stone fabrication shops and analysis of nearly 300 RCS air samples.

The findings underscore the widespread use of ES and the urgent need to improve control methods, including the elimination of dry processing methods, along with repeat RCS sampling to monitor the effectiveness of control methods. The findings also highlight the need for enhanced respiratory protection programs, including respirator fit testing, and more widespread medical surveillance to assess the extent of silicosis in this industry.

Author Contributions

Caitlin M. McGowan assisted with exposure data assessment, data analysis and interpretation, played a primary role in manuscript preparation, and assisted with manuscript revisions. Linda F. Cantley developed the Qualtrics survey, conducted data analyses, and assisted with manuscript preparation and revision. Robert Klein performed exposure data assessment, organization, and interpretation, assisted with data analysis, and assisted with manuscript preparation and revision. Carrie A. Redlich conceived this study and was involved in all aspects of data interpretation, manuscript preparation, and revision.

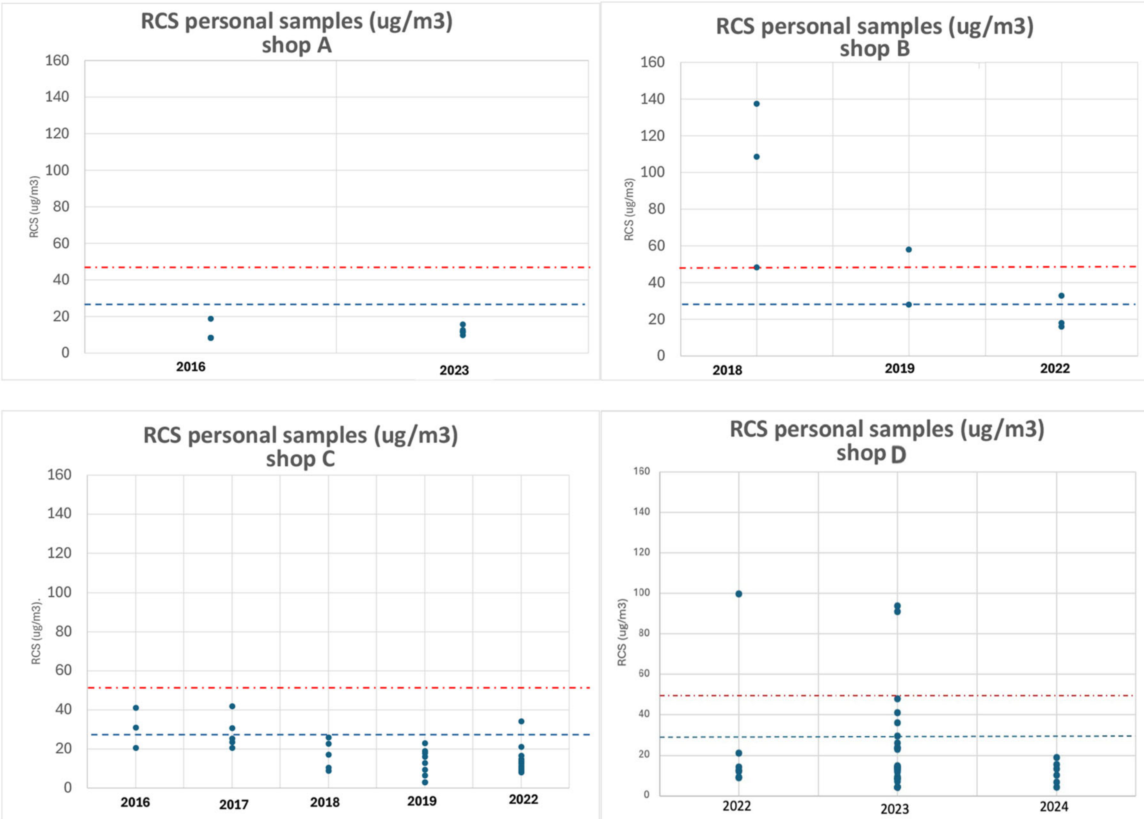

FIGURE 5 | Four Countertop Fabrication shops that submitted RCS sampling over time. Four countertop fabrication shops that submitted repeat RCS sample results over time. Shop A results ($n = 10$) were below the AL in 2016 and 2023. Shop B ($n = 8$) and D ($n = 44$) Elevated RCS exposures in prior years were lower in most recent sampling; Shop C ($n = 35$) results from sampling over 5 years showed no exposure > PEL. ‒ · ‒ · ‒ indicates PEL. ‒ ‒ ‒ ‒ indicates AL. AL = action limit,PEL = permissible exposure limit, RCS = respirable crystalline silica.

Acknowledgments

This study was supported in part by a contract with the NSI and ISFA. These organizations distributed the survey link to and encouraged participation by their member companies, but played no role in data handling, analysis, or the interpretation of the results. The Natural Stone Institute (NSI) and International Surface Fabricators Association (ISFA) distributed the survey link to and encouraged participation by their member companies.

Ethics Statement

The study was approved by the Yale School of Medicine. No personal individual-level data was obtained, so this study did not meet the criteria for human subjects research and was exempt from Institutional Review Board review.

Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.
Figure S1: Distribution of Participating Countertop Fabrication Shops by State. **Table SI:** Sample exclusion criteria. **Table SII:** Respirable Crystalline Silica (RCS) Exposures by Stone Type (ug/m3). **Table SIII:** Respirable Dust (RD) Sample DistribuXon by Similar Exposure Group (SEG) and Controls.

Figure S1: Distribution of Participating Countertop Fabrication Shops by State

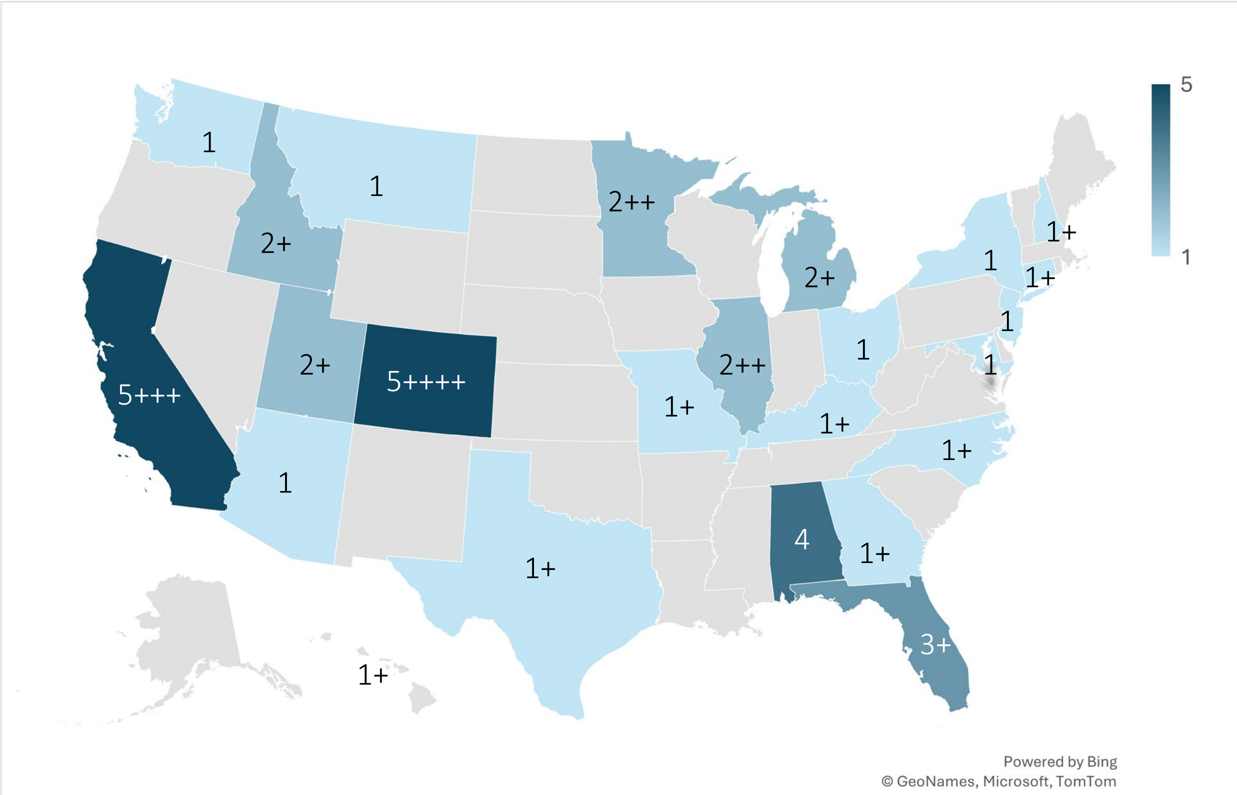

Figure S1 Legend: geographical distribution of the 42 countertop fabrication shops from 24 states that submitted Respirable Crystalline Silica sample results. The number of participating shops per state ranged from 1 to 5 as shown by the numbers in each state. The + signs illustrate the number of participating shops that reported ever having an OSHA inspection. The 4 Canadian shops are not depicted.

+, ++, +++, ++++, indicate one, two, three, or four shop(s) reported ever having an OSHA inspection

Table SI: Sample exclusion criteria

	Number of Samples	Number of shops
	336	55
Rationale for exclusion from analysis		
sampling problems	8	1
no results provided	5	1
report indicates simulated work only	2	
sample duration less than 2 hours	10	1
unable to calculate 8-hr TWA for RCS	14	4
uninterpretable results, such as RCS>RD	5	2
Total excluded	44	9
Number of Samples / Shops used for analysis	292 (86.9%)	46 (83.6%)

Table SII: Respirable Crystalline Silica (RCS) Exposures by Stone Type (ug/m3)

Stone Type	n (%)	Range	AM	GM	< 25 ug/m^3 n (%)	≥ 25 ug/m^3 ≤ 50 ug/m^3 n (%)	> 50 ug/m^3 n (%)
Engineered Stone (ES)	29 (9.9)	2.9 - 63.0	14.7	11.2	25 (86.2)	3 (10.3)	1 (3.5)
Natural Stone (NS)	21 (7.2)	2.9 - 25.5	10.4	8.7	20 (95.2)	1 (4.8)	0
Mix of ES & NS	122 (41.8)	2.9 - 5100.0	83.6	14.6	92 (75.4)	18 (14.8)	12 (9.8)
Not Given (NG)	120 (41.1)	2.8 - 170.0	26.1	15.7	83 (69.2)	23 (19.2)	14 (11.7)
total	292 (100.0)						

Abbreviations: RCS = Respirable Crystalline Silica; ES = Engineered Stone; NS = Natural Stone; AM = arithmetic mean; GM = Geometric mean; NG = Not Given

Table SIII: Respirable Dust (RD) Sample Distribution by Similar Exposure Group (SEG) and Controls

Sample Type	SEG and Controls	Respirable Dust (ug/m^3)			
		n	Range	AM	GM
Area	Non-Shop	3	62.1 – 332.1	153.0	110.2
	Shop	20	43.2 – 235.8	110.2	101.7
Not Given	Not Given – Wet	32	29.7 – 300.0	110.2	98.0
Personal	Large Tools				
	Dry	2	84.9 – 170.0	127.4	120.1
	LEV	1	450.0		
	Wet	45	22.2 – 1590.0	168.9	114.2
	Wet and wall exhaust	2	25.9 – 27.8	26.8	26.8
	Small Tools				
	Dry	6	250.0 – 6800.0	2417.5	1115.2
	LEV	1	1300.0		
	NG	7	44.9 – 260.0	76.2	58.4
	Wet	56	27.6 – 890.0	159.4	119.5
	Wet and wall exhaust	3	24.5 – 38.4	33.2	32.6
	Wet and dry	1	168.0		
	Not Given				
	LEV	1	260.0	260.0	260.0
	Wet	26	29.7- 506.3	203.4	149.3
	Installation	3	62.0- 580.0	264.0	175.4
	Material Handling	6	30.4- 134.8	84.0	71.6
	Support	3	29.0- 87.0	63.8	57.5
Totals		218			

Abbreviations: RD = Respirable Dust; SEG = Similar Exposure Group; AM = arithmetic mean; GM = Geometric mean; LEV = Local Exhaust Ventilation; NG = Not Given