Development of custom calibration factors for respirable silica using standard methods compared to photometric monitoring data

The goal of this study was to investigate the relationship between particulate matter (PM) concentrations recorded by real-time monitors and respirable crystalline silica, in the form of quartz, (RCS) concentrations measured by the standard NIOSH 7500 method using an aluminum cyclone attached to a filter-cassette. Development of correction factors for real-time monitoring instruments would provide instant estimates of RCS concentrations in order to more immediately assess worker exposures and efficacy of controls implemented for worker health and safety. Sampling occurred in two environments: (a) during iron casting at a foundry in the Western United States and (b) in a controlled testing environment, using Arizona Test Dust (ATD) in a low-speed wind tunnel. Two DustTrak DRX 853 monitors were used to collect area samples of PM1, PM2.5, PM4, PM10 and PMtotal, and two SidePak AM510 monitors were used to collect personal samples of PM2.5. Calculated r-squared (R^2) values analyzed how well paired data from real-time monitors and filter-based methods fit a line of regression, and how well real-time monitor measurements predicted RCS concentrations. Among the different PM size fractions recorded by the DRX monitors, the highest coefficient of determination was between RCS quantified by XRD and PM10 for DRX-1 and DRX-2 (both $R^2 = 0.80$), however, their respective regression equations differed. The coefficients of determination calculated for each SidePak were 0.19 and 0.016 respectively, demonstrating a poor ability for these monitors to predict RCS concentrations. There was variability among the identical real-time monitors, especially among the regression equations. Results of this study indicate that it is reasonable to determine a calibration factor for DRX direct-read monitors, enabling them to estimate concentrations of RCS in real-time. Dust containing quartz percentages that are significantly different would require calculation of separate calibration factors. Successful development of silica-dust calibration factors from this study is not intended to replace either the OSHA or NIOSH standard silica sampling and analytical methods. Future work in this area should include using test material with a known, homogenous concentration of silica in a controlled environment to more accurately determine device-specific calibration factors.

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INTRODUCTION

Crystalline silica (SiO_2) is one of the earth's most abundant compounds and is widely used by a range of industries, everything from construction to glass to jewelry production to dental laboratories.[1] Given the ubiquity of silica, and that many work processes involving silica (e.g., drilling, crushing, cutting, sawing) create respirable-sized particles (<5 μm in aerodynamic diameter),[2] the Occupational Safety and Health Administration (OSHA) estimates that up to 2.3 million U.S. workers are exposed to respirable silica.[3] Inhalation of dust containing elevated concentrations of respirable crystalline silica (RCS), in the form of quartz, may lead to silicosis, pneumoconiosis, chronic bronchitis, emphysema, chronic obstructive pulmonary disease (COPD), an increase of lung infections,[2,4] and even death with unmitigated exposure.[5] The U.S. National Toxicology Program (NTP)

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recognizes RCS as a carcinogen,[6] and the International Agency for Research on Cancer (IARC) classifies RCS as a Group 1 carcinogen due to ample evidence of lung carcinogenicity in humans.[7,8] A 2002 systematic literature review conducted by the National Institute for Occupational Safety and Health (NIOSH) also found that RCS exposure increased workers' risks for diseases of the airways, lung cancer, and pulmonary tuberculosis.[4]

OSHA first established a permissible exposure limit (PEL) for RCS exposure in general industry in 1971. This PEL defined the maximum acceptable percentage of respirable dust containing RCS, in the form of quartz,[9] that workers could be exposed to over the course of the workday without incurring negative health effects.[10] In 2013, OSHA conducted a review of the current standard, including input from stakeholders and an extensive review of scientific evidence, and found that RCS exposure at the 1971 PEL still presented a health danger[1] and new industries (e.g., faux stone fabrication and hydraulic fracking) were increasing the number of exposed workers.[11] For this reason, OSHA issued a final rule on June 23, 2016 lowering the allowable exposure to RCS in occupational settings.[1] The new general industry silica standard has a PEL of 50 μg of RCS per cubic meter of air (50 $\mu g/m^3$) averaged over an 8-hour work shift, and an action limit (AL) of 25 $\mu g/m^3$.[1,11] Compliance to the new standard is required begin June 23, 2018 for general industry, maritime, and hydraulic fracturing.[1] The construction industry will be required to comply with the new regulation beginning June 23, 2017.[1] OSHA estimates that once the requirements of the new regulation are in full effect, the lower exposure limit will save more than 600 lives and prevent over 900 new cases of silicosis each year.[11]

The current standard sampling and analytical method used for RCS exposure assessment, i.e., NIOSH Method 7500, results in a time delay of several days due to the requirement of laboratory analysis (i.e., geographic location between the lab and sampling site and workload of the lab). Worker's potential exposure to unknown concentrations of RCS is thus prolonged while waiting for sampling results. The use of real time monitors would provide an improved exposure assessment method that ensures workers are not over-exposed to hazardous levels of RCS in the workplace. Other studies have also examined if real-time methods are as efficient at quantifying respirable dust as established standard filter-based gravimetric methods. Kim et al. compared two such methods, which simultaneously measured concentrations of fine particles ($PM_{2.5}$) that boilermakers were exposed to in their occupational settings, resulting from welding fumes and residual fuel oil ash.[12] It was concluded that $PM_{2.5}$ concentrations recorded by the DustTrak DRX real-time monitor were well correlated to traditional measurements ($R = 0.68$), and linear regression models showed that the log-transformed DRX $PM_{2.5}$ data were highly predictive of log-transformed gravimetric $PM_{2.5}$ data ($R^2 = 0.71$).[12] However, results of this study suggested that the relationship between the two method's measurements of $PM_{2.5}$ could be affected by aerosol particle characteristics, and it is recommended to recalibrate the DustTrak as detailed by the manufacturer.[12]

Another study conducted in the Northeastern United States compared indoor $PM_{2.5}$ concentration values collected by several real-time monitors to concentration values obtained from two filter-based methods. There was high agreement between DustTrak DRX readings and pDR-1500 filter measurements, represented by Spearman's coefficient of correlation value of 0.863.[13] In that study it was found that real-time monitors were convenient for short time scales, but output of accurate aerosol mass concentrations was instrument dependent.[13]

With acceptable agreement between direct-read instruments and filter-based sampling models for $PM_{2.5}$ having been demonstrated by previous investigations, extrapolation of RCS concentrations from real-time monitors may be possible. For example, in evaluating respirable dust as a surrogate for respirable quartz during hydraulic fracking, concentrations of $PM_{1\text{-}4}$ and PM_4 measured from a DustTrak DRX 8533, GK2.69 cyclone, and nylon cyclone were compared. The highest coefficient of correlation for RCS ($R^2 = 0.847$) was between the nylon cyclone and DustTrak $PM_{1\text{-}4}$.[14] Respirable silica data were also well correlated between the nylon cyclone and DustTrak PM_4 ($R = 0.847$).[14] It was therefore suggested that measurements recorded with the DustTrak DRX might be useful in estimating respirable quartz concentrations.[14]

The development of custom calibration factors for real-time monitors would make them a comparable method of exposure assessment to the NIOSH 7500 method, which would benefit both the employer and employee. Employers would have instant access to data providing estimations of RCS during daily operations. With this information they could prioritize the need for further sampling to obtain better data accuracy. In addition, real-time estimates of RCS would be useful in evaluating the efficiency of implemented controls. Employees could also receive instant reassurance that their work environment has low concentrations of silica. Therefore, the purpose of this study was to develop custom calibration factors for respirable silica (quartz) concentrations using two different portable TSI direct-read instruments for dusts containing silica. Successful development of calibration factors would enable real-time evaluation of this important occupational health hazard, including assessment of the effectiveness of implemented engineering controls meant to protect worker health and safety. Successful development of silica-dust calibration factors from this study is not intended to replace either the OSHA or NIOSH standard silica sampling and analytical methods. Secondly, instrument calibration factors are dependent on the fluctuating amount of silica contained in dusts.

MATERIALS AND METHODS

Field Evaluation

All field samples were sampled at a centrifugal casting pipe foundry in the Western United States with known elevated concentrations of RCS in the dust resulting from sand used in processes. Silica laden dust was generated at this facility by several procedures involving sand including charge preparation, melting, molding and mold assembly, core making, shakeout and despruing, accessional use of compressed air and grinding procedures. Area and personal samples were collected (with IRB approval) using both direct-read instruments and filter-cassette sampling methods outlined by NIOSH Method 7500. Five (5) total sampling events occurred at this location over a span of sixteen days in 2016. Events lasted from 4 to 6 hours depending on the operator's schedule.

Real-time particulate area samples were collected using two (2) TSI DustTrak DRX Aerosol Monitor 8533 monitors (hereafter referred to as DRX for this study) (TSI Inc., Shoreview, MN, USA), which is a light scattering laser photometer that simultaneously measures mass concentrations of PM_1, $PM_{2.5}$, PM_4, PM_{10}, and PM_{total} (range of 1–15 μm) size fractions.[15] Area samples were collected near active centrifuge-casting machines where known high levels of RCS had been identified through prior sampling.

Real-time particulate personal samples were collected using two (2) SidePak Personal Aerosol Monitor AM510 (TSI Inc., Shoreview, MN, USA), which are laser photometers.[16] The SidePak monitors used a nylon Dorr-Oliver cyclone pre-separator with a cut point of 4 μm, meaning particles at an aerodynamic diameter of 4 μm will be captured and measured at 50% efficiency. Smaller sized particles will be captured and measured at a higher efficiency. Both SidePak monitors were also equipped with a 2.5 μm impactor. During each sampling event, the two SidePak monitors were placed on two separate casting operators with the connected Dorr-Oliver cyclone attached to the front lapel of the uniform. Participants consented to participating in the study, but were not given any compensation for their cooperation.

To conduct traditional sampling of RCS, using NIOSH Method 7500,[17] an aluminum cyclone attached to a cassette holding a polyvinyl chloride (PVC) filter (5 μm pore size), was used for paired gravimetric sample collection. AirChek XR5000 sampling pumps (SKC Inc., Eighty Four, PA) were set at a flow rate of 2.5 L of air per minute (L/min) to achieve a cutpoint of 4 μm. Filters were prepared, pre-weighed, and post-weighed by ALS Laboratory Group (Salt Lake City, UT,).

Each real-time monitor simultaneously sampled alongside a standard gravimetric sampler in order to produce paired data. Aluminum cyclones (connected to gravimetric filter-cassettes) were attached to the front lapel of operator's work uniforms beside or in close proximity to the Dorr-Oliver cyclones (connected to the SidePak monitors). Standard gravimetric samplers were also placed in close proximity to the DRX monitors to collect area samplers, with the aluminum cyclones being less than 30 centimeters (cm) away from the DRX inlet. Gravimetric pump flow rates were checked using a Bios Drycal Defender 510 (MesaLabs, Lakewood, CO, USA) pre- and post-sampling to ensure the target flow rate (2.5 L/min) was maintained throughout the sampling event. Flow rates of gravimetric area sampling pumps were also checked every hour, while flow rates of sampling pumps worn my operators were checked as often as possible without disrupting work tasks. Real time monitors were wiped down after each sampling event.

Real-time monitors measured and recorded the mass of particulates per volume of air (mg/m^3) at different time intervals. Both DustTrak DRX monitors measured and recorded particulate mass per volume every 6 s. SidePak-1 (serial number ending in 1007) measured and recorded particulate mass per volume every 60 s, while SidePak-2 (serial number ending in1032) measured and recorded particulate mass per volume every second. After sample collection, PVC-cassette media filters were physically transported, following acceptable chain-of-custody procedures, to ALS Laboratories for total respirable dust (NIOSH Method 0600) and silica quartz (NIOSH Method 7500) analysis via X-ray diffraction (XRD).

A lower than expected presence of RCS was seen after receiving analytical results back from ALS Labs. Implemented engineering controls (i.e., fans and ventilation) aimed to decrease concentrations of respirable particulates, and keep operators cool during hot work tasks, had the potential to reduce RCS concentrations below limits of detection, inhibiting the goal of the study. Further sampling interference may have occurred during temporary shut-downs required to complete casting machine maintenance and during the frequent worker breaks taken by operator study participants in areas assumed to have minimal particulate exposure. Therefore, it was determined that a second, controlled environment was required in order to more fully investigate the relationship between data provided by the two sampling methods.

Laboratory Evaluation

In order to conduct testing in a more controlled environment, a low speed wind tunnel[18] was used for a laboratory evaluation of the relationship between the standard gravimetric filter-cassette method and direct-read photometric monitors. Prior to conducting this investigation, the low speed wind tunnel was assessed for its ability to meet all technical requirements for this particular study, and proper data integrity procedures and quality assurance/quality control (QA/QC) procedures were established.

Arizona Test Dust (ATD) (Powder Technology Inc., Arden Hills, MN), with a 69–77% nominal silica content, as indicated by the manufacturer's accompanying safety data sheet (SDS), was chosen as the test material in the wind tunnel. Bulk samples were sent to both ALS Laboratories and Galson Laboratories, Inc. (East Syracuse, NY, USA) for confirmation of silica content. The belt rate of the particle generator was set at 0.5% in order to represent typical levels of silica in an occupational setting. Theoretically, high silica concentration of the test dust would ensure the limit of detection (LOD) would be exceeded even during short duration runs. Again, all real-time monitors used for sample collection were set to a density factor of 1.0, and were not adjusted for the density of ATD (density = 2.5–2.7 g/cm^3).

A total of 5, 1-hour sampling events were conducted in the wind tunnel. The same area and personal real-time monitors and corresponding aluminum cyclone gravimetric samplers used at the foundry were placed in the working section of the wind tunnel. Aluminum cyclones were attached to the front label of the mannequin inside the working section of the wind tunnel, no more than 30 cm away from the corresponding DRX monitor's inlet (Figure 1). Due to physical space limitations, the two (2) SidePak monitors and two (2) corresponding aluminum cyclone samplers were placed on the backside of the mannequin. Specifically, one (1) Dorr-Oliver cyclone and one (1) aluminum cyclone-cassette assembly were attached to each shoulder of the mannequin's back collar (Figure 1). Gravimetric pump flow rates were checked using the Bios Drycal pre- and post-sampling to ensure the target flow rates (2.5 L/min) were maintained. All real-time monitors used for sample collection were set to a density factor of 1.0, and were not adjusted for the density of pure silica (density = 2.65 g/cm^3),[19] and were wiped down after each sampling event.

Statistical Analysis

Values of respirable quartz below the LOD as determined by ALS Lab were imputed in an attempt to reduce the bias from a censored distribution.[20] The LOD for respirable quartz using XRD (0.010 mg/sample) was divided by the volume of air (m^3) drawn through the sampler over the duration of the sampling event. That product was then divided by the square root of 2, as follows

$$\frac{\mathrm{LOD}(\mathrm{mg/m^3})}{\sqrt{2}} \tag{1}$$

Additionally, total respirable dust concentrations that were estimated to be below the LOD (0.020 mg/sample) were also calculated as described using Eq. (1).

All PM measurements recorded by each real-time monitor and paired PVC-cassette filter (quartz) values were organized in Excel (Microsoft Corporation, Redmond, WA) spreadsheets. Statistical analysis was completed using StatPlus (AnalystSoft Inc., Walnut, CA, USA). Simple linear regression was used to analyze the relationship between paired data, and provide an equation that could be used when attempting to predict RCS concentrations using direct reading instruments. In all regression models, the dependent variable was the real-time monitor's concentration value, while the independent variable was RCS concentration values obtained from use of the standard filter-based method. A significance level (α) of 0.05 was chosen in order to achieve a confidence interval (CI) of 95%. How well the data fit the line of regression was estimated by calculation of the R-squared (R^2) value, also known as the coefficient of determination.

The arithmetic mean of PM_1, $PM_{2.5}$, PM_4, PM_{10} and PM_{total} concentrations recorded by the DRX monitors over the sampling duration were used when comparing to RCS concentrations quantified by the standard filter based method using XRD. Similarly, the arithmetic mean of $PM_{2.5}$ concentrations recorded by SidePak monitors over the sampling duration were used for comparison to RCS concentrations quantified by standard filter based methods using XRD. Data were analyzed based on instrument, not sampling location, as the objective was to investigate if the specific real-time monitor measurements could be used to estimate concentrations of RCS. There were a total of 35-paired data sets: 9 for DRX-1, 10 for DRX-2, and 8 for each of the SidePak monitors. DRX-1 experienced battery failure during a sampling event conducted at the foundry resulting in one less set of paired data (n = 9). The SidePak monitors also experienced battery failures resulting in two less sets of paired data for SidePak-1 and SidePak-2 (n = 8).

RESULTS

Table 1 presents PVC-filter respirable dust and quartz data and paired data for DRX-1 (n = 9). Three (3) values from the PVC-filter cassette sampling data were estimated to be below the

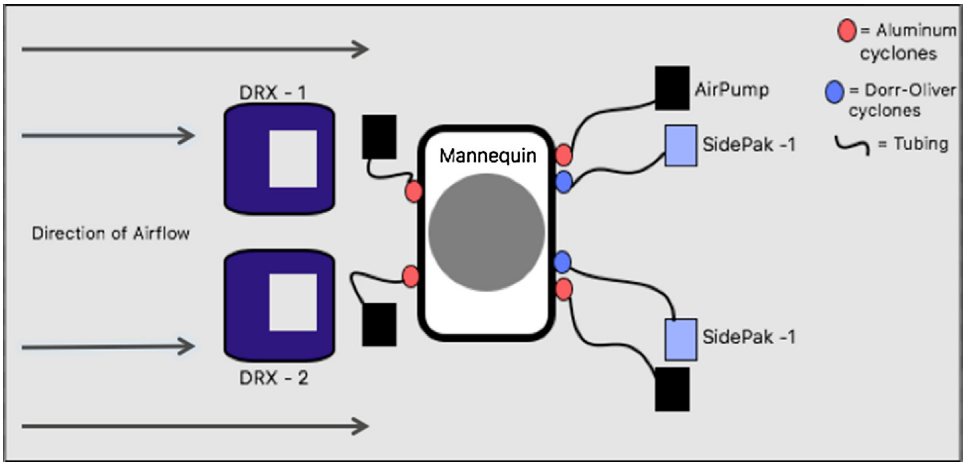

Figure 1. Birds eye view of the working section of the wind tunnel with monitors and standard sampling trains.

Table 1. PVC Filter Respirable Dust and DustTrak DRX-1 Particulate Data.

Location	PVC Filter Respirable Dust					DustTrak DRX-1 Particulate Data				
	Total Dust (mg/m^3)	Quartz (mg/m^3)	Total Dust (mg)	Quartz (mg)	Quartz (%)	PM_1 (mg/m^3)	$PM_{2.5}$ (mg/m^3)	PM_4 (mg/m^3)	PM_{10} (mg/m^3)	PM_{total} (mg/m^3)
Foundry	2.20	0.044	0.583	0.012	2	0.03	0.21	0.39	0.71	1.72
Foundry	4.70	0.024	2.775	0.014	1	0.02	0.23	0.42	0.82	2.25
Foundry	2.50	0.026	1.258	0.013	1	−0.002	0.051	0.103	0.206	0.539
Foundry	0.02[a]	0.013	0.014	0.010	N/A[b]	0.01	0.03	0.06	0.17	0.5
Wind tunnel	0.64	0.085	0.099	0.013	13	0.09	0.18	0.45	1.87	3.32
Wind tunnel	0.57	0.046[a]	0.087	0.007	8	0.02	0.17	0.52	1.97	3.8
Wind tunnel	0.75	0.100	0.116	0.015	13	0.06	0.23	0.64	2.48	5.07
Wind tunnel	0.42	0.073	0.065	0.011	17	0.04	0.23	0.71	2.7	5.39
Wind tunnel	0.09[a]	0.100	0.014	0.015	N/A[b]	0.07	0.28	0.81	3.27	6.86

[a] Concentration estimated below the LOD by ALS lab. Value imputed using Eq. (1).

[b] Quartz percentages unable to be accurately calculated due to respirable dust concentrations below LOD.

LOD and required imputation: two (2) for total respirable dust, and one (1) for respirable quartz. Table 2 displays paired data for PVC-filter respirable dust and quartz data and DRX-2 data (n = 10), and no values required imputation.

Tables 3 and 4 illustrate paired data resulting from PVC-filter respirable dust and quartz data and for SidePak-1 (n = 8) and SidePak-2 (n = 8), respectively. For SidePak 1, one (1) concentration value for respirable quartz resulting from the PVC-filter cassette sampling method was estimated to be below the LOD, and required imputation. SidePak-2 paired data required imputation of two (2) total respirable dust values, and three (3) respirable quartz values resulting

Table 2. PVC Filter Respirable Dust and DustTrak DRX-2 Particulate Data.

Location	PVC Filter Respirable Dust					DustTrak DRX-2 Particulate Data				
	Total Dust (mg/m^3)	Quartz (mg/m^3)	Total Dust (mg)	Quartz (mg)	Quartz (%)	PM_1 (mg/m^3)	$PM_{2.5}$ (mg/m^3)	PM_4 (mg/m^3)	PM_{10} (mg/m^3)	PM_{total} (mg/m^3)
Foundry	1.30	0.029	0.695	0.016	2	0.57	0.6	0.63	0.71	0.75
Foundry	1.70	0.024	1.000	0.014	1	0.69	0.73	0.76	0.88	0.94
Foundry	0.90	0.023	0.463	0.012	3	0.171	0.182	0.191	0.221	0.236
Foundry	0.05	0.016	0.038	0.013	33	0.08	0.09	0.09	0.13	0.14
Foundry	0.04	0.011	0.040	0.010	25	0.06	0.06	0.06	0.08	0.09
Wind tunnel	0.62	0.093	0.096	0.014	15	0.54	0.62	0.74	1.23	1.25
Wind tunnel	0.77	0.089	0.117	0.013	12	0.49	0.58	0.71	1.06	1.08
Wind tunnel	0.89	0.087	0.135	0.013	10	0.77	0.88	1.06	1.76	1.81
Wind tunnel	0.58	0.079	0.088	0.012	14	0.61	0.71	0.86	1.36	1.4
Wind tunnel	0.86	0.100	0.130	0.015	12	0.74	0.86	1.04	1.7	1.75

Table 3. PVC Filter Respirable Dust and SidePak-1 Particulate Data.

Location	PVC Filter Respirable Dust					SidePack-1 Particulate Data
	Total Dust (mg/m^3)	Quartz (mg/m^3)	Total Dust (mg)	Quartz (mg)	Quartz (%)	$PM_{2.5}$ (mg/m^3)
Foundry	0.61	0.022	0.363	0.013	4	0.45
Foundry	2.80	0.048	1.510	0.026	2	0.91
Foundry	0.19	0.130	0.026	0.018	68	0.46
Foundry	1.40	0.042	1.006	0.030	3	0.57
Foundry	0.09	0.008[a]	0.085	0.007	8	0.29
Wind tunnel	0.54	0.210	0.082	0.032	39	0.18
Wind tunnel	0.67	0.120	0.085	0.015	18	0.16
Wind tunnel	0.40	0.084	0.052	0.011	21	0.18

[a] Concentration estimated below the LOD by ALS lab. Value imputed using Eq. (1).

Table 4. PVC Filter Respirable Dust and SidePak-2 Particulate Data.

Location	PVC Filter Respirable Dust					SidePack-2 Particulate Data
	Total Dust (mg/m^3)	Quartz (mg/m^3)	Total Dust (mg)	Quartz (mg)	Quartz (%)	$PM_{2.5}$ (mg/m^3)
Foundry	0.52	0.029	0.293	0.016	6	0.675
Foundry	0.02[a]	0.046	0.014	0.027	N/A[b]	1.21
Foundry	0.42	0.029	0.208	0.014	7	0.202
Foundry	0.36	0.025	0.266	0.019	7	0.314
Foundry	0.54	0.022	0.485	0.020	4	0.332
Wind tunnel	0.34	0.046[a]	0.052	0.007	13	0.223
Wind tunnel	0.26	0.047[a]	0.039	0.007	18	0.201
Wind tunnel	0.09[a]	0.047[a]	0.014	0.007	N/A[b]	0.223

[a] Concentration estimate below LOD by ALS lab. Value imputed using Eq. (1).

[b] Quartz percentages unable to be accurately calculated due to respirable dust concentrations below LOD.

from the PVC-filter cassette sampling method.

Overall, 5 of the 35 concentration values for respirable quartz were estimated to be below the LOD (14% of the data), and required imputation using Eq. (1). Similarly, four (4) of the 35 concentration values for total respirable dust were estimated to be below the LOD (11% of the data) and also required imputation (Eq. (1)). In situations where total respirable dust was estimated to be below the LOD while RCS was quantified, the percentage of quartz could not be accurately calculated.

Simple linear regression analysis was completed to investigate the predictability of real-time monitor measurements for RCS concentrations. Table 5 presents the results for each DustTrak-1 size segregated mass concentrations compared to RCS concentration values resulting from use of the standard method using an aluminum cyclone sampling train. DRX measurements of PM_{10}, PM_1, and PM_{total} were highly predictive of RCS concentrations ($R^2 = 0.80$, 0.78, and 0.76 respectively), and all were statistically significant ($p < 0.05$). Comparison between real-time PM_4 measurements and results determined from using the filter-based method were most relevant, as the aluminum cyclone has a cut-point of 4 µm. Those data fit the line of regression well ($R^2 = 0.70$) and were also significantly predictable of RCS concentrations. The poorest agreement was seen between DRX-1 $PM_{2.5}$ measurements and RCS concentrations that resulted from the NIOSH 7500 method ($R^2 = 0.48$), but the regression was determined to be statistically significant (p-value = 0.036).

Similarly, analysis of paired data resulting from the DRX-2 monitor and PVC-cassette filters were overall predictive of RCS concentration values (Table 6). The strongest agreement was between real-time measurements of PM_{10}, PM_{total}, and PM_4 ($R^2 = 0.80$, 0.79, and 0.60 respectively). These comparisons were also determined to be statistically significant ($p < 0.05$). Paired data comparing DRX-2 $PM_{2.5}$ measurements to RCS concentrations had a moderate fit to the line of regression ($R^2 = 0.53$), and comparison using DRX-2 PM_1 measurements showed poor fit to the line of regression ($R^2 = 0.45$). However, linear regression results of both of the DRX-2 size fractions were determined to be statistically significant.

Table 7 displays linear regression results for both SidePak monitors when compared to RCS concentrations determined using the standard sampling method. Real-time measurements recorded by both SidePak monitors related very poorly to RCS concentrations quantified by the filter-based method ($R^2 = 0.19$ and 0.016). The analysis of each set of paired data

Table 5. Simple Linear Regression Results for DustTrak DRX-1 Data Compared to RCS Data Resulting From Use of the Aluminum Cyclone Standard Method.

DustTrak DRX-1	N = 9		
Particle Size	R^2 value	p-Value	Equation
PM_1	0.78	0.001	y = 0.02 + 0.99x
$PM_{2.5}$	0.48	0.036	y = 0.008 + 0.28x
PM_4	0.70	0.005	y = 0.007 + 0.11x
PM_{10}	0.80	0.001	y = 0.02 + 0.03x
PM_{total}	0.76	0.002	y = 0.01 + 0.01x

Table 6. Simple Linear Regression Results for DustTrak DRX-2 Data Compared to RCS Data Resulting From Use of the Aluminum Cyclone Standard Method.

DustTrak DRX- 2	N = 10		
Particle Size	R^2 value	p-Value	Equation
PM_1	0.45	0.033	y = 0.01 + 0.09x
$PM_{2.5}$	0.53	0.016	y = 0.007 + 0.09x
PM_4	0.60	0.005	y = 0.005 + 0.08x
PM_{10}	0.80	0.0005	y = 0.006 + 0.05x
PM_{total}	0.79	0.0007	y = 0.005 + 0.05x

Table 7. Simple Linear Regression Results for SidePak-1 and SidePak-2 Data Compared to RCS Data Resulting From Use of the Aluminum Cyclone Standard Method.

Monitor	N = 8		
	R^2 value	*p*-Value	Equation
SidePak-1	0.19	0.29	$y = 0.12 - 0.11x$
SidePak-2	0.016	0.76	$y = 0.03 + 0.004x$

was also found to not be statistically significant.

DISCUSSION

Results from this study indicate that specific particle size fraction concentrations measured with the DustTrak DRX real-time monitor could be used to estimate concentrations of RCS. Both sets of PM_{10} paired data for these instruments demonstrated the best fit with the respective line of regression. However, the best-fit line equations for the identical instruments differed, indicating inter-instrument variability.

It was indicated prior to conducting sampling at the site that concentrations of respirable quartz regularly exceeded the PEL, however, the results obtained in this study demonstrated lower values, which may indicate interference of on site controls. Area samples collected at the foundry could have been affected by natural ventilation of fresh air, e.g., outdoor air moving from one end of the foundry to the other, facilitated by the building's structural design. As to not interfere with daily operations, and reduce risk to researchers and operators, area samples were collected on the north side of the caster where incoming air was freshest. Casting operators at the foundry exposed to hot work environments were additionally required to wearing layers of protective gear necessary to prevent accidental burns. In an attempt to mitigate heat stress, industrial fans and other engineering controls were implemented, which had the potential to lower respirable dust concentrations in the worker's breathing zone. Other controls, specifically frequent shift rotation intended to reduce risks associated with hot work, also potentially affected data collection. It was assumed operators spent their shift breaks in a location were respirable dust concentrations were low potentially affecting results, and the determined performance of the SidePak monitors at predicting RCS concentrations, which is this study was poor. SidePak monitors were not turned off during these shift breaks to avoid further interference with daily operational tasks.

In the wind tunnel tests, additional interference of measurements collected by SidePak monitors and corresponding standard sampling trains could have occurred. Although the wind tunnel provides a controlled environment, which is less subject to variability and has an aerosol injection that provides uniform concentrations,[18] airflow patterns may have been affected by the number and spatial proximity of instruments in the working section of the wind tunnel. Due to size limitations of the working section, SidePak monitors and corresponding standard sampling trains were placed on the backside of the mannequin (Figure 1), which is where airflow disruption may be higher. Variability in data could have arisen from these factors, translating into poor agreement between the two samplers.

Bulk samples of ATD sent to two different commercial laboratories were determined to have silica (quartz) concentrations closer to 12–17% respectively, as opposed to the 69–77% concentration level indicated on the manufacturer's chemical safety data sheet (SDS), see Table 8. Even with the lower percentage of silica (quartz) present, it was assumed that the LOD should have been exceeded during all wind tunnel sampling events, however, RCS concentrations were estimated below the LOD for all three (3) sampling events for SidePak-2 and one (1) event for DRX-1. However, the percentage of quartz varied between samplers, as illustrated by Table 9.

Table 8. Arizona Test Dust (ATD) Silica (Quartz) and Other Components.

	Silica (%Quartz)	Cristobalite (%)	Tridymite (%)	Element Oxides (%)
SDS (Arizona Test Dust ATD)	69–77	NA[a]	NA	23–31
ALS lab (bulk ATD)	12	<1.0	<1.0	NA
Galson lab (bulk ATD)	17	<1.2	<0.98	NA

[a] NA = not analyzed.

Table 9. Filter Cassette Quartz Descriptive Statistics Associated with DRX 1, DRX-2, SidePack-1 and 2.

PVC-Filter Cassette (Quartz) Descriptive Statistics; DRX-1 & DRX-2 (N = 17 Above LOD)	
Average	10.7%
Standard deviation	9.0
Max	33%
Min	1%
Range	32%
PVC-Filter Cassette (Quartz) Descriptive Statistics; SidePack-1 & SidePack-2 (N = 14 Above LOD)	
Average	15.6%
Standard deviation	18.1
Max	68%
Min	2%
Range	66%

Table 10. Filter Cassette Quartz Descriptive Statistics Associated with Foundry and Wind Tunnel Sites.

Foundry Filter-Cassette Quartz Descriptive Statistics (N = 17 Above LOD)	
Average	10.4%
Standard deviation	17.2
Max	68%
Min	1%
Range	67%

Wind Tunnel Filter-Cassette Quartz Descriptive Statistics (N = 14 Above LOD)	
Average	15.9%
Standard deviation	7.5
Max	39%
Min	8%
Range	31%

The average percent of respirable quartz for the filter-cassette data associated with the DRX-1 and DRX-2 instruments was 10.7% with a standard deviation of 9.0 (N = 17 above LOD). The average percent of respirable quarts for the filter-cassette data associated with the SidePack-1 and SidePack-2 instruments was 15.6% with a standard deviation of 18.1 (N = 14 above LOD). The range of (1%–25%) for the DRX filter-cassette quartz data and 2%–68% for the SidePack filter-cassette quartz data, see Table 9, could indicate some laboratory analytical error, but could also stem from the heterogeneous nature of silica in the particles sampled, giving rise to inconsistencies when analyzed by XRD. Additionally, the average percent of respirable quartz for filter-cassette data associated with the foundry sampling site was 10.4% with a standard deviation of 17.2 (N = 17 above LOD) and the average percent of respirable quartz for the filter-cassette data associated with the wind tunnel sampling was 15.6% with a standard deviation of 18.1 (N = 14 above LOD), see Table 10. Consequently, the average respirable quartz filter-cassette data associated with DRX instruments (10.7%), SidePack instruments (15.6%), foundry site (10.4%), and the wind tunnel (15.6%) are similar in percentage and were determined to be similar; therefore, the data could be used for statistical evaluations. However, if the average percent of respirable quartz had been significantly different between sampling sites combining quartz data for statistical evaluations to determine calibration factors would be erroneous. In summary, dust containing quartz percentages that are significantly different would require calculation of separate calibration factors. Additional studies will be conducted to determine concentration zones for the percent of quartz contained in dust (0–35%, 36–75%, 76–100%; 0–25%, 26–50%, 51–75%, 76–100%) that will provide statistically significant calibration factors.

Despite running into complications and discrepancies during sampling, this study was able to investigate the performance of real-time monitors compared to the standard method for measuring RCS in two different environments: an occupational setting (foundry) and a laboratory setting (wind tunnel). Although the total sample number was low, there is data on a wide range of different particle size fractions that could be investigated relative to respirable quartz concentrations.

CONCLUSIONS

The results of this study indicate it would be reasonable to assume a calibration factor could be determined to predict concentrations of RCS using real-time monitors. There was good agreement between both DRX PM_{10} measurements and PVC-cassette filter quartz concentrations ($R^2 = 0.80$). However, the degree of agreement between other particulate size fractions and RCS (quartz) concentrations varied between the identical instruments. Also, the regression equations enabling prediction of RCS were not similar for the identical instruments, indicating variability between instruments as well. Arguably, the strongest relationship when comparing the two methods is between DRX-1 PM_1 concentration measurements and RCS concentrations determined by XRD. Not only does the data fit the line of regression well ($R^2 = 0.78$), but the regression equation implies that the read out is nearly 1 to 1, indicating the concentration of PM_1 is essentially the same as the concentration of RCS ($y = 0.02 + 0.99x$).

Agreement between paired data resulting from the SidePak measurements and traditional RCS sampling was very poor, but could have been affected by engineering controls at the foundry and airflow disruptions in the wind tunnel. Further investigation with a larger sample number could more confidently define a calibration factor, making these real-time monitors more effective at predicting concentration of RCS in real-time. Future investigations using test materials with a known, homogeneous silica content in a controlled environment where generation of particulate concentrations can be controlled, could also better establish calibration factors, potentially enabling real-time monitors to predict levels of RCS in the workplace.

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