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Review Article

Correlating Exposure to Respirable Crystalline Silica (RCS) with Loss of Lung Function: Treatment of Data and Statistical Analysis

Kevin Hedges[1*], Susan Reed[1,2], Robert Mulley[1]

[1]Western Sydney University, Australia

[2]Edith Cowan University, Australia

***Corresponding Author:** Kevin Hedges, Western Sydney University, Australia.

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Abstract

In a study looking at potential impact to respiratory health of quarry workers exposed to airborne respirable crystalline silica (RCS) in Queensland, Australia, respirable dust exposure sampling was undertaken using the method specified in AS 2985-2009. Analysis of the collected samples for alpha quartz was carried out using infrared spectroscopy. Lung function tests for the exposed workers at each quarry were conducted using an Easyone® spirometer. The aim of this study was to determine whether increased RCS exposure is associated with a reduction in lung function. Personal RCS exposures were pooled into similar exposure groups (SEGs), minimum variance unbiased estimates (MVUE), were plotted against the forced expiratory volumes in one second (FEV1) % of predicted for corresponding SEGs. Non-linear correlations were observed including natural log and polynomial function. Estimated (full shift) exposures pooled for each Similar Exposure Group (SEG) correlated with lung function measured as FEV1 % of predicted ($p<0.05$) as confirmed by the Kolmogorov goodness of fit test. Furthermore a trend test using SAS 9.4 resulted in $p = 0.0013$. A major finding for those workers exposed to RCS at 0.1 mg/m^3 was loss of lung function greater than 20%. The increased loss of lung function was positively correlated with jobs associated with increased RCS exposure. When similar exposure groups were combined into three RCS exposure ranges categorised as high (≥ 0.09 - ≤ 0.20 mg/m^3), medium (≥ 0.04 - ≤ 0.08 mg/m^3) and low (< 0.04 mg/m^3), analysis of variance (ANOVA) confirmed that the loss of lung function below the lower limit of normal (LLN) at 0.1mg/m^3 TWA-8hrs, is significant ($p < 0.05$).

A major finding from this study predicts that an abnormal loss of lung function may occur even when workers are exposed to RCS where the occupational exposure limit (TWA) is 0.1 mg/m^3 or greater which is the case in many jurisdictions.
Keywords: Respirable Crystalline Silica; lung function; quarries

Introduction

A Number of studies have demonstrated that there is a loss of lung function in quarry and stone workers resulting from exposure to respirable crystalline silica (RCS) [1-3]. A joint project coordinated through Western Sydney University (WSU) and Queensland Department of Mines and Energy (DME), assessed the risk of silica exposure in quarries, dimension stone mines and a silica sand mining / processing operation in Queensland, Australia. Hedges et al [4] demonstrated that 8 of 13 similar exposure groups (SEG) including quarries, a stone forming mine and sand processing site, exceeded the Safe Work Australia Exposure Standard (TWA) for respirable crystalline silica of 0.1 mg/m^3. Most of the SEG$_s$ were shown to have a log-normal distribution, which indicated representative exposures typical for these activities. Hedges et al [5] then reported RCS exposure for 47 workers across 9 quarries, including dimension stone and sand processing operations. In that study there was a correlation of reduced lung function against RCS exposure.

Forced Expired Volume of exhaled air in 1 Second (FEV1), which is a sensitive measure of lung function loss was considered the best predictor [6], and early warning, about the onset of more serious lung function decline. Forced expired volume in 1 second (FEV1) is the volume expired in the first second of maximal inspiration and a measure of how quickly full lungs can be emptied [6]. In this study the measured FEV1 percentage of predicted is compared with the RCS exposure measurements for the same workers. This approach will allow for direct comparison and pooling of workers into SEGs to investigate whether a dose response curve was observed at a group level. The analysis [5] indicated a significant decline in FEV1 % of predicted at the Safe Work Australia Exposure Standard.

In the current paper the exposure response data points are grouped into tertiles to increase statistical power by allowing analysis of variance (ANOVA) with increased sample numbers.

Methodology

Respirable Crystalline Silica (RCS)

Personal exposure monitoring was undertaken on 47 workers across 9 quarries, including dimension stone and sand processing operations. Personal samples were collected according to AS2985-2009 [7] using a SKC cyclone sampling head attached to a sampling pump at a flow rate of 2.2 (±5%) L/min using SKC AirCheck 2000 Model 210-2002 sampling pumps. The pumps were calibrated using a TSI 4100 series (Serial No.4146 0629 001) mass flow meter. The TSI secondary flow-meter was calibrated against a primary soap film flow-meter as per appendix B of AS2985-2009. [7] A correction factor was calculated and all sampling volumes were adjusted to align with the primary standard. The dust samples were collected on SKC GLA-5000 PVC 25mm 5 µm pore size filters. The analysis of samples for respirable silica was undertaken at the Safety in Mines Testing and Research Station (SIMTARS) laboratories in Queensland in accordance with the method published by National Health and Medical Research Council [8] in their document "Methods for Measurement of Quartz in Respirable Dust by Infrared Spectroscopy". Exposure standards for respirable dust and respirable silica were adjusted by applying the Brief and Scala model using the average weekly hours adjustment equation as recommended by Safe Work Australia [9]:

$$RF = \frac{40}{h} * \frac{168 - h}{128}$$

Where: h = average hours worked per week over full roster cycle.

Lung Function Testing (Spirometry)

Lung function testing was undertaken on-site using an Easyone® spirometer (Model 2001, Serial No 66033/2008). The method used followed the method described by Miller et al. [10] The spirometer prediction parameter was set on NHANES III, the system interpretation was GOLD/Hardie, and the best value result was used for interpretation. The parameters measured and recorded included:

- FEV1 (Forced Expired Volume in 1 Second) measured in Litres, which is the volume of air exhaled in the 1st second.
- FEV1 % of predicted.
- FVC (Forced Vital Capacity) measured in Litres, which is the total amount of air exhaled.
- FEV1/FVC is the ratio of the two measures (%) and provides an indication of airflow obstruction.

This paper discusses results for FEV1 % of predicted.

Study Site Selection

The intention was to collect cross sectional representative samples both geographically and geologically. To understand whether there is a dose response between exposure to RCS and loss of lung function, sites were selected with low, medium and high crystalline silica (quartz) in the rock as shown in Table 1.

Study Site Code	Operation	Region of Queensland	Silica content
A	Dimension sandstone mine	South	High
C	Sand processing, screening plant	South	High
FV	Aggregate, rock and sand (andesite)	Central	Medium
F_o	Sand, soil and gravel	Central	Medium
H	Aggregate	Central	Unknown
N	Sand processing, screening plant	South	High
P	Sand, soil and gravel	North	High
R	Dimension sandstone mine	South	High
Y	Hornfels and basalt rock	Central	Low

Table 1: *Study sites, regions and silica content based on geology for each site.*

Statistical Analysis

Hedges et al. [5] demonstrated a significant difference between exposures of (SEGs) to RCS natural log (LN) where transformed mean confidence intervals were calculated and compared. A statistically significant difference in RCS exposure between SEGs was verified using analysis of variance for all measured exposures.

This paper has therefore focussed on:

- those similar exposure groups (SEGs) that are log normally distributed,
- a sample size of at least 6 and
- geometric standard deviations less than 3.

Data censoring has therefore been applied where statistical analysis has been carried out on only those exposure groups that meet these criteria.

Further analysis is provided, where SEGs were categorised into three groups as high - A (RCS ≥0.09 - ≤0.20 mg/m^3), medium - B (RCS ≥0.04 - ≤0.08 mg/m^3), and low - C (RCS <0.04 mg/m^3) exposure bands for follow up statistical analysis using Analysis Of Variance (ANOVA).

Results

Table 1 shows the ranking of each operation based on the geology of rock extracted. Table 2 shows SEGs and estimated average exposures (as minimum variance unbiased estimates - MVUE) for each. SEGs that are log-normally distributed are considered representative of each SEG when the geometric standard deviation (GSd) was less than 3. Two sample groups that were found to be log-normally distributed did not meet the criteria of a SEG as the GSd was greater than 3. Five SEGs had sample sizes too small for analysis of log normality.

Similar exposure group (SEG)	N	Estimated average (MVUE)	Upper confidence limit (UCL)	Geometric standard deviation GSd	Log normal distribution LN	Lung function FEV1 % of predicted
Wet plant**	6	0.01	0.02	1.43	*	103
Rear dump**	8	0.02	0.03	1.9	*	90
Excavator crusher	3	0.02	N/A	1.74	IS	ND
Dozer	3	0.03	ND	1.58	IS	ND
Loader**	32	0.03	N/A	2.41	Yes	84
Electrician	2	0.04	N/A	1.23	IS	98
Saw	6	0.04	0.14	2.26	No	90
Excavator**	12	0.05	0.08	2.13	Yes	83
Environmental officer	3	0.07	0.31	1.49	IS	86
Crusher	9	0.09	0.14	1.68	No	79
Loader crusher	9	0.11	2.25	5.16	Yes	85
Excavator and saw**	9	0.11	0.33	2.51	Yes	75
Service	3	0.13	N/A	2.72	IS	80
Stonemason	3	0.27	N/A	3.94	IS	69
Fitter	11	0.29	5.87	6.2	Yes	86
Sand Plant Operator	12	0.29	0.36	1.48	No	92

Notes

(IS): Insufficient sample size.

(*): At least 50% of samples are at or below limit of quantitation.

N/A: Due to insufficient sample size the upper confidence limit was not determined.

MVUE: Minimum variance unbiased estimate which is an estimated average of a log-normal data set.

UCL: Lands exact upper confidence limit.

GSd: Geometric standard deviation.

Table 2: *Summary of RCS and lung function results.*

For SEGs with a minimum of 6 samples, which are log-normally distributed and have a GSd less than 3, there was a significant difference between SEGs. When all of the data were analysed, as shown in Table 2, there appears to be a downward trend in respiratory function in RCS concentrations up to 0.11 mg/m^3. For exposures above 0.20 mg/m^3 the same trend is not observed.

As reported by Hedges et al [5], validation was provided by analysis of variance (ANOVA) shown in table 6, to show that there is a significant difference in RCS exposure between SEGs (p = 0.0007). Hedges et al [5] also noted that ANOVA failed to show the same similar significant difference between SEGs for FEV1 % of predicted. The data were further analysed to understand why a similar difference in lung function between SEGs cannot be demonstrated. The quality of spirometry is important and the Easyone® spirometer provided a quality score after each assessment. Table 3 shows that the majority (57%) of respiratory results were classified as precise. (Note: An "A" reading test result corresponds to a good quality (precise) assessment whereas "D" is sub-standard.)

Quality reading	Number
A	25
B	9
C	3
D	5
F	2

Table 3: *Shows the quality of test results.*

The appropriate data for ANOVA were obtained by selecting at least 3, workers from each SEG shown in Table 4. Larger sample sizes are preferred because they provide a better estimate of inter-individual variability. To strengthen the ANOVA with increased sample size, similar exposure groups were grouped into three distinct bands shown in Table 5. The groups were low (group C) < 0.04 mg/m^3, medium (group B) ≥ 0.04 - ≤ 0.08 mg/m^3, and high (group A) ≥ 0.09 - ≤ 0.20 mg/m^3. All distributions were shown to be log-normal with the exception of RCS for group C due to results close to the limit of quantitation and small sample size. Therefore upper and lower confidence limit values cannot be determined for this data set.

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
Crusher	3	236	78.6667	5.333333
Excavator	4	330	82.5	4.333333
Loader	9	760	84.4444	311.2778

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	75.8611	2	37.9306	0.196149	0.82428	3.80557
Within Groups	2513.89	13	193.376			
Total	2589.75	15				

Table 4: *ANOVA carried out for FEV1 % of predicted for SEGs with at least 3 different workers.*

Group	Similar exposure groups	Range of estimated average RCS exposures mg/m³	Estimated average MVUE mg/m³	UCL LCL (GSd)	Average maximum FEV1 % of predicted	UCL LCL (GSd)
A	Excavator + saw Crusher	≥ 0.09 - ≤ 0.20 mg/m³	0.13	0.20 0.10 (2.0)	76	87 68 (1.2)
B	Loader/excavator crusher Excavator Loader Saw	≥ 0.04 - ≤ 0.08 mg/m³	0.05	0.06 0.04 (2.4)	84	89 80 (1.2)
C	Rear dump Sand plant wet	< 0.04 mg/m³	0.02	-	95	107 86 (1.1)

Table 5: *Grouping SEGs to improve ANOVA*

Table 5 indicates differences between the RCS ranges and shows that there is reduced lung function capacity as the RCS range (or exposure band) increases. ANOVA, between the three groups was carried out to confirm that these differences, for both FEV1 %, are real and unlikely to occur by chance as shown in table 6 and 7. Grouping data showed significant differences ($p<0.05$) between groups A, B and C for both RCS mg/m³ and FEV1 % of predicted as shown in Tables 6 and Table 7 respectively.

SUMMARY				
Groups mg/m³	*Count*	*Sum*	*Average*	*Variance*
≥ 0.09 ≤ 0.20 (A)	16	2.11	0.13187	0.008896
≥ 0.04 ≤ 0.08 (B)	64	2.94	0.04594	0.002504
< 0.04 (C)	14	0.33	0.02357	7.09E-05

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.11317	2	0.05659	17.62809	3.38E-07	3.09655
Within Groups	0.29211	91	0.00321			
Total	0.40528	93				

Table 6: *ANOVA for RCS for groups A, B, C*

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
76 (UCL 87 LCL 68) A	6	456	76	128
84 (89 UCL 80 LCL) B	18	1511	84	144
95 (107 UCL 86 LCL) C	5	474	95	121

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	966	2	483	3.519	0.044	3.369
Within Groups	3570	26	137			
Total	4536	28				

Table 7: *ANOVA for FEV1 % of predicted for groups A, B, C*

Analysis of SEGS confirmed that the loss of lung function, below the lower limit of normal (LLN) at the current SWA-ES, is unlikely due to chance (ANOVA, $p < 0.05$).

Discussion

Spirometry can be used to assess lung function, and can also be used to differentiate obstructive (such as COPD) from restrictive respiratory disease, which includes silicosis. The most commonly seen pathological defect is airflow obstruction, which is characterised by reduced expiratory flows (for example COPD and asthma).

To understand the level of inter-individual variability and distribution of lung function tests for SEGs, a minimum number of workers are required for each SEG. In this study one of the shortcomings in lung function testing was that there was a limited number of workers in some SEGs. A larger operation with similar mineralogy and a greater number of workers would allow a better analysis of variance. Nevertheless, the Kolmogorov goodness of fit test has shown that the curvilinear relationship between FEV1 % of predicted and RCS exposures up to 0.13 mg/m^3 is significant.

Harper et al. [12] reported that analysis of Proficiency Analytical Testing (PAT) results between 2003 and 2013 indicated that the variation in RCS analysis is less than it was in the period 1990–1998. Harper et al. [12] qualified their findings by saying that it was partly because of a change in sample production procedure and because the colorimetric method had been phased out, although quality improvements in the x-ray diffraction (XRD) or infrared (IR) methods may have also played a role. Harper et al also noted that matrix interference does not lead to biases or substantially larger variances for either XRD or IR methods. PAT samples are not produced below 40 μg and variance may increase with lower masses. PAT data from lower mass loadings will be required to evaluate analytical performance if exposure limits are lowered without change in sampling method. [12] Using the current sampling method, AS2985-2009 [7], for task specific exposure measurement may not result in a filter mass loading greater than 40 μg. The mass (40 μ g.) is the minimum loading required for accurate RCS determination. This may necessitate that samples be collected with a validated cyclone and sampling pump capable of sampling at higher flow rates [13].

This study conducted "full shift" personal exposure monitoring which results in a higher degree of accuracy for exposures above 0.05 mg/m^3. Using PAT as a benchmark more analytical validation work is required to assess the uncertainty of RCS mass loadings at less than 40μg. This is particularly important when determining the limit of quantitation for RCS against EN 482 [13] as shown in Table 6.

EN 482 [13] requires that the relative expanded uncertainty be determined at 0.1 or 10% of the Occupational Exposure Limit (OEL). Using the current sampling and analytical methodology this standard limits a further reduction in the Safe Work Australia 8 hr time weighted exposure standard of 0.1 mg/m^3. In contrast to the EN 482:2012 requirement [14] findings from this study indicate that loss of lung function can occur at an occupational exposure limit 8 hr TWA of 0.1mg/m^3.

Harper et al. [12] indicated that where sampling durations are reduced to estimate "task exposure" then cyclones, shown to match the collection efficiency curve with higher flow rate pumps should be used. This study also demonstrated "a case in point" that occupational exposure limits must not be viewed as "fine dividing lines" between safe and unsafe exposure.

Factor	Comment	Situations
Particle size	Enhances potency	Grinding and abrasive processes
Dry and freshly cut	Reference point to compare potency	Drilling, crushing
Wetting	From dust suppression	Wet extraction processes
Aged	Reduces potency	No abrasion or grinding
Presence of clay	Aluminium reduces potency	Mines extracting low rank coal

Table 8: *Potency matrix*

(Adapted from HSE [11] p.7)

	Measuring range	Relative expanded uncertainty
Short-term (eg 15 min)	0.5 to 2 times limit values	≤ 50%
Long-term	0.1 to < 0.5 times limit value	≤ 50%
Long-term	0.5 to 2 times limit value	≤ 30%

Table 9: *BS EN 482:2012 Workplace exposure - General requirements for the performance of procedures for the measurement of chemical agents (p.8).*

Conclusion

A decline in lung function has been shown at an occupational exposure limit (8hr-TWA) of 0.1 mg/m^3. Grouping the SEGs into tertiles allowed an ANOVA demonstrating significant differences ($p<0.05$) for FEV1 % of predicted between tertile bands.

To further confirm the findings from this study, a replicated larger study with a greater number of workers in each similar exposure group (SEG) will allow a more robust analysis of variance. In addition, sampling RCS at a higher flow rate will improve the sensitivity of analysis by ensuring that the mass loading of RCS on filters is greater than 40μg.

Although, there is a limited sample size, this study has demonstrated the value of correlating RCS exposures at a similar exposure group (SEG) level with loss of lung of lung function and then further enhancing the statistical analysis by grouping SEGs into tertiles. Broadening this study, across mining and along with other industries including construction, will allow further method refinement, and lead to a greater understanding in the variability of dose response in different sectors at different RCS exposure concentrations.

There are approximately 55,000 workers employed in Queensland mining, and about 268,000 in the Australian mining industry. Mining directly employs 2.3% of the total Australian workforce, and accounts for 10.2% of Australia's Gross Domestic Product (GDP) [14].

Health surveillance and personal exposure RCS monitoring over time (longitudinally) will add to the weight of evidence that respiratory health is being impacted by exposure to RCS in some industries, particularly mining. Using FEV1 % of predicted at the lower limit of normal (LLN) of 80% provides a useful screen for further investigation. This may link RCS exposure with loss of lung function which will provide the impetus for risk reduction. The recently published guidance by the Health and Safety Executive (HSE) for occupational health surveillance for those exposed to RCS provides a useful reference [15].

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Volume 1 Issue 2 September 2021