Accepted: 16 May 2017
DOI: 10.1002/ajim.22740

RESEARCH ARTICLE

WILEY AMERICAN JOURNAL OF INDUSTRIAL MEDICINE

Trends in exposure to respirable crystalline silica (1986-2014) in Australian mining

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Funding information
Australian National Health and Medical Research Council, Grant number: 1069535; WA Institute of Respiratory Health

Background: Respirable crystalline silica (RCS) has been associated with severe health risks. Exposures in Western Australia (WA) have been typically high in hard-rock mining and have reduced substantially since the mid-1900s. We described trends in RCS exposure in WA miners over the past 30 years.

Methods: A total of 79 445 reported personal RCS exposure measurements, covering the years 1986-2014, were examined. Mixed-effects models were applied to estimate RCS exposure levels, including spline terms to estimate a time trend.

Results: An overall downward trend of about −8% per year was observed for RCS exposures in WA mining. Highest RCS exposure levels were modeled for base metal mining and exploration settings. Drilling occupations were among the highest exposed jobs.

Conclusion: RCS exposure levels have fallen considerably in the last three decades. However, there are still mining occupations that may need further attention to avoid adverse health effects in these workers.

KEYWORDS
miners, occupational exposure, personal exposure, quartz, temporal trend

1 | INTRODUCTION

Respirable crystalline silica (RCS) exposure has been associated with severe health risks, namely lung cancer,[1] silicosis,[2] and other non-malignant respiratory diseases (ie, chronic bronchitis and chronic airflow obstruction),[3,4] as well as renal disease[5] and autoimmune disorders.[6]

Occupational exposure to RCS is common in a range of industries, such as mining, construction, pottery, and foundries. At a population level, reported proportions of workers exposed to RCS range from 2.3% in the European Union (1990-1993) and Canada (2006) to 6.6% in Australia (2012).[7–9]

A review by Creely et al[10] showed that overall reported occupational exposure levels are decreasing over time worldwide. For RCS exposure, annual changes between −7% in Chinese mines and potteries between 1950 and 1987[11] and −11% for silica sand plants (1974-1996) in the United States[12] were reported.[10] Modeling of personal RCS exposure measurements (1976-2009) from Europe and Canada, across a wide range of industries, indicated an overall annual trend of −6% in exposure levels.[13]

High levels of exposure to RCS, with a median average of 0.43 mg/m^3, have been reported for Western Australian (WA) gold miners in the mid-1900s[14] and the risk of silicosis has been particularly high among underground workers, with a standardized mortality ratio of 16.1 (95% confidence interval (CI) 12.8-20.2).[15] An Australian occupational exposure limit of 0.2 mg/m^3 for RCS was introduced in the 1970s, primarily to reduce the risk of silicosis.[16] A decline in RCS exposure levels over time has been described for WA metalliferous miners overall, with geometric mean (GM) exposure levels falling from 0.12 mg/m^3 in 1977-0.03 mg/m^3 in 1993.[17] Since 2005, the exposure limit has been 0.1 mg/m^3 as an 8 h time-weighted average.[18] While silicosis risk may have been virtually eliminated in WA, lower levels of exposure to RCS in the mines may still cause other lung diseases.

Using an industry-wide exposure database with monitoring data from 1986 to 2014, we explored whether the level of exposure to RCS in the WA mining sector has continued its downward trend.

2 | METHODS

In WA, the State's Department of Mines and Petroleum maintains an exposure database on a wide range of contaminants that are relevant in the mining industry.[19] Mining companies are required to sample atmospheric contaminants and report results to the Department. Following risk assessment, sampling quota are set for each mine site, aiming to collect a representative sample of the exposure conditions. The number of samples requested per job depends on the size of the mine. Sample results with details on company, worker, and sampling method have been systematically recorded since 1986, as we have described before.[20] For current analyses, RCS exposure measurements from June 1986 to January 2015 were available. Measurements from 2015 (n = 17) were combined with 2014.

Collection and analyses of respirable dust samples were performed according to the Australian Standard (AS 2985), using cyclones for gravimetric dust sampling. The RCS content was determined by either X-ray diffraction or infra-red spectroscopy, but it was not recorded in the database which one of the methods was used. In total, 82 830 personal exposure measurement results were reported for RCS. The corresponding concentration of total respirable dust was known for 81% of these samples, which allowed for the calculation of the silica content. Samples taken for less than 240 min (n = 64) and samples taken for longer than 840 min (n = 3 120) were excluded, as well as samples collected with an inadequate device (n = 31) and measurements from unknown mine types (n = 11). Results exceeding the upper limit of RCS determination (n = 106) were set at 2.5 mg/m^3.[21] We excluded a further 148 samples because of unreliable results (ie, the RCS content exceeding 100% of the reported respirable dust concentration for the same sample), leaving 79 445 measurements for analyses.

Concentrations were summarized as arithmetic mean (AM), GM and geometric standard deviation (GSD). RCS concentrations were log-normally distributed and analyses were performed on the log-transformed data. Imputation techniques were used to replace values below the limit of detection (LOD; 41% of all samples), following the method described by Lubin et al.[22]

The PROC MIXED restricted maximum likelihood method in SAS v9.4 (SAS Institute Inc. Cary, NC) was used to develop the statistical model to describe the data and we compared the Akaike information criterion (AIC) for model selection. Fixed effect terms included a spline time trend for year of sampling (b-spline with four knots and three degrees of freedom, derived with PROC TRANSREG), mine type based on mineral mined (gold; nickel; iron ore; base metal (lead/copper/zinc); industrial minerals; other minerals, and exploration), sampling duration (in minutes), and measurement reason (quota or additional sampling). Job title and mine site ID were included as random effects. Worker identification numbers were not assigned to measurements pre-2000, and therefore, not included in the model. The "other mineral" mining group mainly consisted of bauxite (39% of measurements in this group) and tin/tantalum/lithium (33%) mining.

3 | RESULTS

GMs ranged from 0.037 mg/m^3 in 1986-1990 to 0.006 mg/m^3 in 2011-2015 and the highest levels were observed for base metal mining (0.020 mg/m^3), followed by exploration and gold mining, with GMs of 0.016 and 0.014 mg/m^3, respectively (Table 1). Jobs with the highest RCS exposure levels included underground winding and hoisting operators (GM 0.031 mg/m^3), exploration drillers (0.021 mg/m^3), and ore samplers (0.020 mg/m^3). The RCS content of total respirable dust was also relatively high for these jobs (medians 4.3-5.4%) compared with the overall median of 3.3%.

Overall, 16% of RCS measurements were taken when the worker was wearing some form of respiratory protective equipment (RPE) (Table 1). This proportion increased over time, ranging from 8% in 1986-1990 to 19% in 2011-2015. RPE was mainly used in exploration settings (56%). Jobs with highest reported use were exploration drillers (44%) and ore samplers (46%). Workers who made least use of RPE included excavation operators (3%), mobile plant operators (3%), drivers (3%), material handling occupations (4%), and general underground miners (5%). No correlation with level of exposure was observed for percentage respirator use at an occupational group level (R_P = 0.28).

RCS exposure levels have reduced considerably between 1986 and 2000 (Fig. 1). In the last 10 years, levels have flattened. The highest RCS exposures were estimated for base metal mining, with GMs of 0.081, 0.018, and 0.009 mg/m^3 in 1986, 2000, and 2014, respectively (Table 2). Nickel mining showed the lowest levels, with 0.035, 0.008, and 0.004 mg/m^3 in the same years.

Estimated RCS exposure levels for 12 h shifts for the ten highest exposed jobs (with at least 10 measurements available) are shown in Table 3. These levels were standardized to the reference category of gold mining, representing the largest part of the data (44%). The highest levels were estimated for railway track laying and maintenance: with 0.165 and 0.018 mg/m^3 in 1986 and 2014, respectively.

4 | DISCUSSION

Clear downward trends were observed for RCS exposure in the WA mining industry between 1986 and 2014, flattening over the last decade. These decreasing exposure levels are likely a result of awareness around the adverse health effects of RCS, changing mining practices, and subsequent improved dust control measures.

Decreasing occupational RCS exposure trends have been reported internationally, ranging from −11% to −6% per year.[10,11,13,23] We included the year of measurement as a spline term in our model, as this

TABLE 1 Summary statistics of respirable crystalline silica (RCS) exposure measurements (mg/m^3) in Western Australian mines

	N	<LOD%	AM	GM	GSD	RPE	RCS content median (IQR)%
Overall	79 445	41	0.043	0.011	4.52	16	3.3 (1.0-10)
Years							
1986-1990	11 084	10	0.101	0.037	4.06	8	-
1991-1995	13 672	13	0.054	0.017	3.88	13	3.3 (1.0-10)
1996-2000	9180	13	0.058	0.016	4.03	15	3.3 (1.4-10)
2001-2005	13 624	67	0.031	0.007	4.56	18	5.0 (3.3-10)
2006-2010	16 379	63	0.021	0.006	3.78	18	3.3 (1.0-10)
2011-2015	15 506	57	0.016	0.006	3.33	19	1.0 (1.0-5.0)
Mine type							
Gold	34 707	31	0.055	0.014	4.68	12	5.0 (1.6-10)
Iron ore	18 122	54	0.024	0.007	3.82	14	1.5 (0.8-5.0)
Industrial minerals	9404	50	0.042	0.011	4.91	12	5.0 (1.0-10)
Nickel	8201	50	0.021	0.008	3.38	26	3.3 (1.0-10)
Base metals	2375	30	0.076	0.020	5.30	13	9.1 (3.3-13)
Other minerals	5050	49	0.042	0.008	4.39	24	3.3 (0.1-10)
Exploration	1586	40	0.075	0.016	5.59	56	4.7 (0.1-10)
Job titles							
Management/administration	1896	56	0.020	0.007	3.68	10	2.5 (0.5-10)
Engineers/professionals	1537	58	0.024	0.007	3.81	26	3.1 (0.5-10)
Blast hole drillers	4560	34	0.060	0.015	4.87	9	5.0 (0.5-15)
Blasting occupations	1909	42	0.046	0.011	4.60	12	3.3 (0.4-10)
Exploration drillers	2854	33	0.108	0.021	6.31	44	5.0 (0.5-13)
Excavation equipment operators	5727	34	0.032	0.011	3.92	3	3.8 (0.5-10)
Mobile plant operators	3377	40	0.035	0.011	4.22	3	3.8 (0.5-10)
Drivers	6781	46	0.026	0.009	3.91	3	5.0 (0.5-10)
Service occupations	1429	53	0.025	0.008	4.03	8	3.3 (0.4-10)
Ore treatment-processing plant operators	13 015	38	0.047	0.012	6.64	20	3.3 (0.3-14)
Ore treatment-mobile plant operators	1515	66	0.020	0.006	3.69	9	5.0 (0.5-10)
Ore treatment-final product handlers	1395	64	0.023	0.006	3.94	29	2.0 (2.5-10)
Ore samplers	6729	29	0.094	0.020	5.75	46	4.3 (0.3-18)
Railway occupations	181	66	0.082	0.009	6.47	22	1.0 (0.3-16)
Metal working trades	6940	55	0.025	0.007	3.91	13	2.0 (0.3-10)
Electrical/electronic trades	1684	58	0.025	0.007	3.63	11	2.0 (0.3-10)
Miscellaneous trades/utilities	1313	67	0.031	0.005	3.81	13	1.0 (0.3-10)
Material handling occupations	522	57	0.013	0.006	2.93	4	1.9 (0.4-10)
Underground miners	3709	24	0.035	0.013	3.82	5	2.6 (0.5-10)
Underground drillers	2230	41	0.028	0.010	3.89	11	3.3 (0.5-10)
Underground loading/transport	7064	31	0.038	0.012	4.15	13	3.3 (0.6-10)
Underground service occupations	1513	41	0.032	0.010	3.95	11	3.3 (0.5-10)
Underground winding/hoisting operators	301	10	0.095	0.031	4.83	7	5.4 (0.7-30)
Underground supervisors	1264	48	0.026	0.008	3.47	11	5.0 (0.6-10)

N, Number of samples; <LOD, limit of detection; AM, arithmetic mean; GM, geometric mean; GSD, geometric standard deviation; RPE, respiratory protective equipment worn at time of measurement; RCS content, RCS content of total respirable dust;IQR, interquartile range.

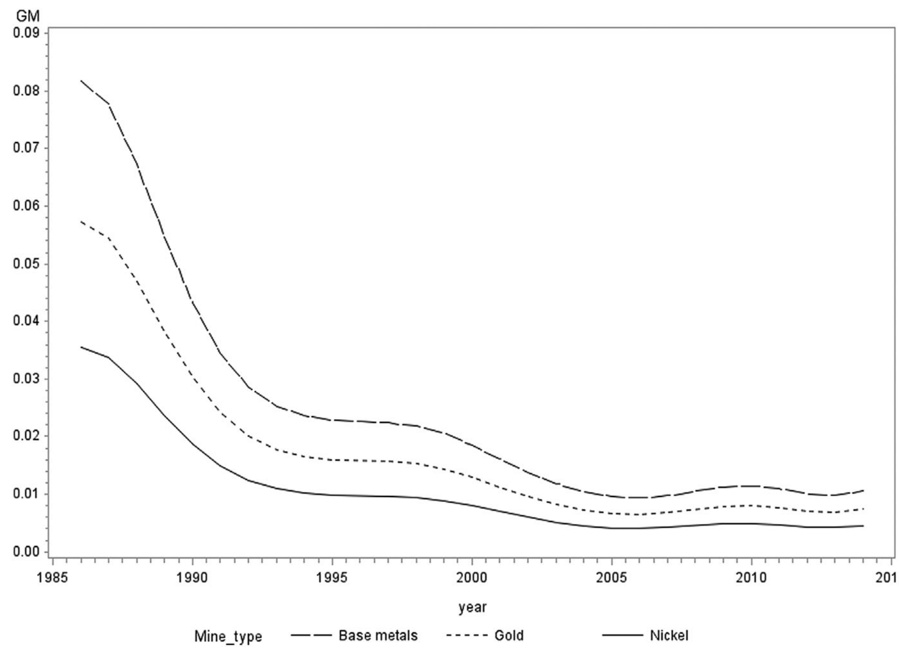

FIGURE 1 Temporal trend in respirable crystalline silica exposure levels (mg/m^3) in the Western Australian mining industry (1986–2014), based on modeled exposure data

gave the best model fit, which complicates a direct comparison with the previous published trends. Running the same model with sampling year as a continuous variable, however, revealed an overall trend of −7.9% per year (data not shown).

Historically, RCS exposure levels were reported to be particularly high in underground gold mining.[24–26] For example, in a cohort of US gold miners, median exposure levels of 0.05 mg/m^3 were reported for underground workers between 1940 and 1965, and 0.15 mg/m^3 for workers who started before 1930, whereas surface workers were considered non-exposed.[26] However, job-specific levels appeared to be comparable between surface and underground mining operations in our dataset. For example, an underground truck driver in 2000 was exposed to an estimated level of 0.011 mg/m^3, where levels for surface truck drivers ranged from 0.009 to 0.014 mg/m^3, depending on the truck's duty (data not shown). Estimated levels for laborers were 0.013 mg/m^3 underground and 0.012 mg/m^3 in a quarry (data not shown). The strong reduction in underground exposure levels of RCS in comparison with the early to mid-20th century may be attributed to improved dust control.[24] The proportion of measurements representing underground and surface occupations is also consistent with comparable exposure situations: only one fifth of RCS measurements in the exposure database represented underground operations, whereas the majority (80%) of the measurements of elemental carbon (to indicate diesel exhaust) were performed during underground operations.[20]

TABLE 2 Estimated RCS exposure levels for 12 h-shifts (in mg/m^3) for the different mine types

Mine type	1986	2000	2014
Gold	0.057	0.013	0.007
Iron ore	0.048	0.011	0.006
Industrial minerals	0.061	0.014	0.008
Nickel	0.035	0.008	0.005
Base metals	0.082	0.018	0.011
Other minerals	0.052	0.012	0.007
Exploration	0.071	0.016	0.009

NB. These estimates resulted from the model adjusted for job title, mine site ID, and measurement reason.

Ore samplers have previously been described as experiencing high RCS exposure levels, based on exposure modeling of European and Canadian data, estimating a GM of 0.09 mg/m^3 for 1998 (ranging from 0.05 to 0.23 by region).[18] For a sample preparation operator (as presented in Table 2), our estimation for 1998 was 0.031 mg/m^3. RCS exposure for a general miner, either surface or underground, was estimated at 0.05 mg/m^3 (range 0.03-0.12) in Europe/Canada.[13] Based on our data, RCS exposure estimates for production and services workers in 1998 gold mining ranged from 0.010 to 0.035 mg/m^3 underground and from 0.010 to 0.037 mg/m^3 above ground (data not shown). Reported RCS levels for specific occupations in US metal and non-metal mines in 2005-2010 were somewhat higher than we estimated, for example 0.043 mg/m^3 for underground crushing operators[27] compared to 0.015-0.018 mg/m^3 for 2005-2010 in our analyses. However, Watts et al[27] described only a slight decrease in RCS exposures between 1993 and 2010, where our levels were higher in the earlier years (eg, 0.040 mg/m^3 for underground crusher operators in 1993).

Ground and roof support occupations (including shotcreters) and diesel loader operators appeared to be among the highest exposed

TABLE 3 Estimated RCS exposure levels for 12 h-shifts (in mg/m^3) for the 15 highest exposed jobs

Job title	1986	2000	2014
Railway track laying and maintenance	0.168	0.038	0.022
Spray painter (motor/engine trades)	0.146	0.033	0.019
Driller's assistant (surface)	0.137	0.031	0.018
Exploration drilling (surface)	0.131	0.030	0.017
Crushing operator (underground)	0.130	0.029	0.017
Blast hole drill operator's assistant (surface)	0.127	0.029	0.016
Sample preparation operator	0.116	0.026	0.015
Conveyor attendant or operator	0.094	0.021	0.012
Driller (surface)	0.090	0.020	0.012
Engineering occupations	0.089	0.020	0.012
Service occupations (underground)	0.082	0.019	0.011
Ground or roof support (underground)	0.082	0.019	0.011
Powder crew laborer	0.081	0.018	0.010
Mechanical bogger driver	0.081	0.018	0.010
Diesel loader operator	0.078	0.018	0.010

NB. These levels are standardised to gold mining (reference category in model), and were adjusted for mine site ID and measurement reason.

occupations to both RCS and elemental carbon.[20] As a consequence of their exposures they may be at a higher risk of lung diseases including lung cancer.[1]

The available information on RPE was very limited. On the sample record sheet there was a "tick box" for respirator "worn" or "not worn," while it was unknown what type of equipment was used and whether it was worn correctly. Interestingly, the data showed no relation between RCS exposure level and use of respirators at the job level. Likewise, comparing the reported RPE over time suggested an increased use, while RCS exposure levels reduced. The RPE may also be worn due to exposures other than RCS, but other potential reasons for more frequent RPE use over time may include growing awareness of occupational hazards in the mining industry and social acceptance of wearing personal protective equipment.

For the earliest samples (pre-1992) we did not have the results for both total respirable dust and RCS. We could therefore not apply the quality check by exceedance of 100% silica content. However, only 0.2% of samples where the content was known were excluded for that reason, suggesting a small potential overestimation of exposure levels in the earlier years. We have previously discussed the representativeness of the measurements in this exposure database[20]: overestimation of exposure levels may have occurred due to monitoring where higher exposure was expected, while levels may have been underestimated due to monitoring in "best practice" mines only. Comparison with the international literature indicates that our findings for specific occupations and time trends in WA mines were in the same order of magnitude.

Overall levels of exposure to RCS in WA mines have reduced considerably over the past three decades and are well below currently legislated occupational exposure limits. However, there are still operations in the contemporary mining industry associated with relatively high exposures to RCS, such as drilling, that may put workers at risk of adverse health effects. Continued surveillance of miners' health is therefore indicated.

ACKNOWLEDGMENTS

The CONTAM exposure database has been provided by the WA Department of Mines and Petroleum, and the authors thank Mike Rowe and David Petersen for their assistance in the data provision.

FUNDING

This work was performed within the scope of projects funded by the Australian National Health and Medical Research Council (NHMRC grant #1069535) and the WA Institute of Respiratory Health (Alan King Westcare grant 2016). LF is supported by fellowships from the NHMRC and Cancer Council Western Australia.

DISCLOSURE BY AJIM EDITOR OF RECORD

Steven Markowitz that he has no competing or conflicts of interest in the review and publication decision regarding this article.

DISCLOSURE (AUTHORS)

The authors declare no conflicts of interest.

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How to cite this article: Peters S, Vermeulen R, Fritschi L, Musk A, Reid A, de Klerk N. Trends in exposure to respirable crystalline silica (1986-2014) in Australian mining. *Am J Ind Med*. 2017;60:673–678. https://doi.org/10.1002/ajim.22740