OPEN ACCESS

Original research

Prevalence and risk factors for silicosis among a large cohort of stone benchtop industry workers

Ryan F Hoy [1,2] Christina Dimitriadis,[1] Michael Abramson,[3] Deborah C Glass [1] StellaMay Gwini [1] Fiona Hore-Lacy,[1,2] Javier Jimenez-Martin,[1] Karen Walker-Bone [1] Malcolm R Sim [1]

► Additional supplemental material is published online only. To view, please visit the journal online (http://dx.doi.org/10.1136/oemed-2023-108892).

[1]Monash Centre for Occupational and Environmental Health, School of Public Health & Preventive Medicine, Faculty of Medicine, Nursing and Health Sciences, Monash University, Melbourne, Victoria, Australia
[2]Department of Respiratory Medicine, Alfred Health, Melbourne, Victoria, Australia
[3]School of Public Health & Preventive Medicine, Faculty of Medicine, Nursing and Health Sciences, Monash University, Melbourne, Victoria, Australia

Correspondence to
Dr Ryan F Hoy, Monash Centre for Occupational and Environmental Health, School of Public Health & Preventive Medicine, Faculty of Medicine, Nursing and Health Sciences, Monash University, Melbourne, VIC 3004, Australia; ryan.hoy@monash.edu

Received 24 February 2023
Accepted 30 May 2023
Published Online First 16 June 2023

ABSTRACT

Objectives High silica content artificial stone has been found to be associated with silicosis among stone benchtop industry (SBI) workers. The objectives of this study were to determine the prevalence of and risk factors for silicosis among a large cohort of screened SBI workers, and determine the reliability of respiratory function testing (RFT) and chest x-ray (CXR) as screening tests in this industry.

Methods Subjects were recruited from a health screening programme available to all SBI workers in Victoria, Australia. Workers undertook primary screening, including an International Labour Office (ILO) classified CXR, and subject to prespecified criteria, also underwent secondary screening including high-resolution CT (HRCT) chest and respiratory physician assessment.

Results Among 544 SBI workers screened, 95% worked with artificial stone and 86.2% were exposed to dry processing of stone. Seventy-six per cent (414) required secondary screening, among whom 117 (28.2%) were diagnosed with silicosis (median age at diagnosis 42.1 years (IQR 34.8–49.7)), and all were male. In secondary screening, silicosis was associated with longer SBI career duration (12 vs 8 years), older age, lower body mass index and smoking. In those with silicosis, forced vital capacity was below the lower limit of normal in only 14% and diffusion capacity for carbon monoxide in 13%. Thirty-six (39.6%) of those with simple silicosis on chest HRCT had an ILO category 0 CXR.

Conclusion Screening this large cohort of SBI workers identified exposure to dry processing of stone was common and the prevalence of silicosis was high. Compared with HRCT chest, CXR and RFTs had limited value in screening this high-risk population.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ High silica content artificial (engineered) stone has rapidly become a popular material used for domestic and commercial benchtops production in many countries and has been associated with increasingly frequent reports of silicosis. Comprehensive screening of stone benchtop industry (SBI) workers including CT chest imaging has demonstrated the ability to detect early-stage disease.

WHAT THIS STUDY ADDS

⇒ This study reports outcomes from real-world protocolised health assessments of a large cohort of SBI workers and confirms an alarmingly high prevalence of silicosis. The study demonstrates that dry processing of artificial stone has been extremely common. Also, the sensitivity and positive predictive values of respiratory function tests and chest X-ray as screening tests to detect silicosis in this high-risk occupational group are inadequate.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Urgent action is required to improve occupational health and safety measures in the SBI. This includes consideration of the role of CT chest imaging for screening, and most importantly the protection of workers from silica exposure.

INTRODUCTION

The first Australian case of silicosis associated with artificial (engineered or reconstituted) stone in the benchtop fabrication industry was reported in 2015.[1] Seven years later, 579 cases were identified in Australia.[2] During the same period, there have been increasingly frequent reports of silicosis in the stone benchtop industry (SBI) internationally.[3–7] In comparison to silicosis associated with natural silica sources (eg, mining), artificial stone silicosis has been found associated with a shorter duration of exposure, more rapid disease progression and higher mortality.[5] Many patients have required lung transplantation and fatalities have been reported.[5 7 8] Despite these health concerns, the use of artificial stone has grown at a rapid rate.[7]

Artificial stone is a composite material, typically containing over 90% crystalline silica mixed with resins and pigments.[9 10] Poor dust control measures have been widely reported in the SBI, in particular the practice of 'dry processing', where water dust suppression is not used during cutting, grinding or polishing of stone.[3 6 7] High intensity power tools used to dry process artificial stone, generate extremely high levels of respirable crystalline silica (RCS).[11 12] In addition to RCS, artificial stone dust may have other toxic properties, including the presence of nano-range sized particles, metal ions and volatile organic compounds, such as styrene and toluene.[13 14]

Check for updates

To cite: Hoy RF, Dimitriadis C, Abramson M, *et al. Occup Environ Med* 2023;**80**:439–446.

Although the artificial SBI has grown at a rapid rate and there have been clear warning signs of serious adverse health effects associated with working in this industry, the prevalence of silicosis among SBI workers had not been previously quantified. Although legally required in many countries, routine health surveillance has generally been lacking in this industry, and many cases have been identified at an advanced stage.[6] There is also concern that respiratory function tests (RFT) and chest X-rays (CXR) used for surveillance of silica-exposed workers have poor sensitivity to detect early stage silicosis in this industry.[15]

We previously reported the methodology of a large protocolised screening programme for SBI workers incepted in the Australian State of Victoria in 2019.[16] In the first year of the programme, 86 workers were diagnosed with silicosis (76% simple silicosis).[16] Higher mean serum ACE levels were present for SBI workers with silicosis compared with those without.[17] A minority of workers reported that they would always wear respiratory protective equipment, or that on tool ventilation was provided.[18]

This study reports outcomes following the completion of the SBI screening programme. The objectives were to (1) determine the prevalence of silicosis in a large cohort of high-risk SBI workers; (2) determine factors associated with increased risk of silicosis and (3) investigate the predictive values of RFTs and CXR to screen high-risk SBI workers for the presence of silicosis.

METHODS

This study was set within a large population-based voluntary screening programme, funded and coordinated by the state Work, Health and Safety (WHS) regulatory agency (WorkSafe Victoria). Recruitment of workers was undertaken by the WHS agency. Methods used to promote the programme include targeted media campaigns, silicosis-specific educational meetings and workplace visits by inspectors. The WHS agency operated a dedicated phone and email service for workers to register with the programme. Screening was offered to any person who had worked in the SBI, for any period of time. Workers were requested to consent to provide details of their health assessments to the study.

Details of the programme methodology and preliminary findings from 239 workers who had participated during the first 12 months of the programme have been previously reported.[16] In brief, a two-stage screening process was developed using a protocolised approach (refer to online supplemental material for further information). All SBI workers underwent primary screening administered by one of two occupational health providers under the supervision of an occupational and environmental physician. Primary screening included a standardised questionnaire, a CXR evaluated according to the International Labour Office (ILO) classification and RFTs (forced expiratory volume in 1 s (FEV_1); forced vital capacity (FVC); ratio of FEV_1/FVC and diffusion capacity for carbon monoxide (D_Lco)). RFTs were performed at one of the nine Thoracic Society of Australia and New Zealand accredited respiratory function laboratories in Victoria.

After completion of primary screening, data were reviewed by an occupational and environmental physician and secondary screening was mandated if one or more of the following criteria were met:

1. Abnormal CXR: ILO small opacity profusion category ≥1 or other relevant abnormal finding.
2. Abnormal RFT result: defined by FEV_1, FVC, FEV_1/FVC or D_Lco below lower limit of normal (LLN), and/or a 12% and 200 mL improvement in FEV_1 and/or FVC post bronchodilator.[19]
3. Symptoms or signs determined by the physician to be significant, such as exertional dyspnoea.
4. 'High' or 'very high' estimated silica exposure category determine by responses to the occupational questionnaire (table 1).

Table 1 Estimated silica exposure categories determined from occupational questionnaire responses

		Duration (years) of work in stone benchtop industry			
		≤2	>2 to ≤4	>4 to ≤6	>6
Highest dry processing exposure intensity reported	Never (0%)	L	L	M	M
	Rarely (1%–9%)	L	L	M	M
	Sometimes (10%–24%)	M	H	H	H
	Frequently (25%–49%)	H	H	H	VH
	Very frequently (50%–99%)	VH	VH	VH	VH
	Always (100%)	VH	VH	VH	VH

Duration (years) was calculated from the current year, or year the worker left the stone benchtop industry, minus the year of commencing work in the stone benchtop industry, or alternatively calculation of cumulative years if work was intermittent. Highest exposure intensity was determined from the response to 'What proportion of time have you spent doing dry work or near someone else doing dry work (bystander) exposure since starting this job?' and identification of the job with the highest exposure regardless of duration.
H, high; L, low; M, medium; VH, very high.

Secondary screening involved a high-resolution CT (HRCT) chest and respiratory physician assessment.

All participants in primary screening were asked to give written informed consent for transfer of their results to Monash University investigators. For workers undergoing secondary screening, the assessing respiratory physician registered the worker on Research Electronic Data Capture (REDCap), including diagnostic information and transfer of investigation reports.[20]

Silicosis diagnosis

Diagnosis of silicosis, determined by the assessing respiratory physician, required the worker to have had a compatible occupational history and HRCT findings consistent with silicosis, in the absence of a more likely alternative diagnosis. Simple silicosis was defined by pulmonary nodules ≤10 mm diameter on HRCT, and complicated silicosis by a nodule(s) or opacity >10 mm diameter on HRCT. Diagnoses reported to the research team were confirmed by one respiratory physician investigator (RFH) by review of the investigations and respiratory physician reports. In the event of disagreement, the assessing respiratory physician was contacted for discussion to confirm the diagnosis.

Data analysis

Rose Dyspnoea Scale score was calculated with one point assigned to each common activity associated with dyspnoea, where a score of 0 indicated no dyspnoea with activity and 3 indicated significant limitations due to dyspnoea.[21] A smoker was defined by a positive response to 'Have you ever smoked as much as one cigarette a day for as long as one year?'. Pack-years were calculated as a product of years of smoking multiplied by average number of 20 cigarette packs smoked daily.

Data were analysed using Stata Statistical Software V.17 (StataCorp). Categorical data were summarised using frequencies with percentages, while continuous/interval data were summarised as means (with SD) or medians (with 25th and 75th percentiles, P25–P75) where data were skewed. χ^2 and Fisher's exact tests were used to examine the relationship between categorical covariates and secondary screening status. Means were compared by independent sample t-tests and Wilcoxon rank-sum tests used when medians were reported. A $p<0.05$ was used for interpreting statistical significance.

Analysis of prevalence and the factors associated with silicosis, and reliability of screening investigations was undertaken among secondary screening participants excluding those who underwent primary screening only and consequently did not have an HRCT chest performed. Prevalence of silicosis was reported as a percentage with 95% Clopper-Pearson binomial CIs. The relationship between silicosis diagnosis (as the dependent variable) and estimates of participant exposure or other participant characteristics was assessed using logistic regression and the results were reported OR and their 95% CIs. Both unadjusted ORs and ORs adjusted for age, body mass index (BMI), smoking status and country of birth were presented. The factors chosen to adjust for in the multiple regression were considered a priori to be the most important confounders. Diagnostic accuracy of CXRs with ILO classification and RFTs was assessed using the diagt command in Stata.

RESULTS

Characteristics of participants

In total, 993 workers attended the screening programme between May 2019 and October 2021. Seven hundred and seventeen workers consented to participate in the study, however, 173 were excluded due to incomplete evaluations or because they had never worked in the SBI (online supplemental figure 1). Of the 544 who completed primary screening, 514 (94.5%) were male with a median age of 36.2 years and less than half (49%) were born in Australia. Table 2 provides further description of participants and shows that those who met criteria for secondary screening were older, had higher BMI and dyspnoea scores, and were more likely to smoke than those who only had primary screening.

In their longest held job, 493 (90.6%) indicated that they worked with both natural and artificial stone. In total, 402 workers reported using artificial stone for over 50% of their

Table 2 Characteristics of participants

	All participants	Primary screening only	Primary and secondary screening
	N=544	N=130	N=414
Sex, n (column %)			
Male	514 (94.5)	113 (86.9)	401 (96.9)
Age (years), median (P25–P75)	36.2 (28.9–45.6)	31.1 (25.0–39.2)	38.1 (30.1–46.7)
BMI* (kg/m^2), mean (SD)	27.4 (5.5)	26.3 (5.1)	27.7 (5.5)
Smoking history, n (column %)			
Never	240 (44.1)	85 (65.4)	155 (37.4)
Former	112 (20.6)	12 (9.2)	100 (24.2)
Current	192 (35.3)	33 (25.4)	159 (38.4)
Place of birth, n (column %)			
Australia	268 (49.3)	56 (43.1)	212 (51.2)
Asia	181 (33.3)	55 (42.3)	126 (30.4)
Europe	47 (8.6)	5 (3.8)	42 (10.1)
Other	32 (5.9)	8 (6.2)	24 (5.8)
Unspecified	16 (2.9)	6 (4.6)	10 (2.4)
SBI career duration (years)			
Median (P25–P75)	7 (3–14)	2 (1–3)	10 (5–15)
Range (min–max)	<1–44	<1–24	<1–44
Time since first SBI job (years)			
Median (IQR)	8 (3–14)	2 (1–3)	10 (6–16)
Age at first SBI job (years)			
Median (P25-P75)	26 (20–33)	29 (23–36)	25 (20–33)
Range (min–max)	13–59	15–59	13–59
Total no of SBI workplaces reported, median (IQR)			
Median (P25–P75)	1 (1–3)	1 (1–1)	2 (1–3)
Range (min–max)	1–30	1–8	1–30
Rose dyspnoea score† (column %)			
0	402 (74.0)	123 (94.6)	279 (67.6)
1	90 (16.6)	6 (4.6)	84 (20.3)
2	31 (5.7)	1 (0.8)	30 (7.3)
3	20 (3.7)	0 (0.0)	20 (4.8)

*Missing data: BMI – 5.
†Modified Rose dyspnoea score 0–3.
BMI, body mass index; P25, 25th percentile; P75, 75th percentile; SBI, stone benchtop industry.

Table 3 Outcomes from secondary screening: silicosis diagnosis status by participant demographic and occupational exposure characteristics

	Silicosis diagnosis		Comparison between groups			
	No silicosis	Confirmed silicosis	Unadjusted analyses		Adjusted analyses*	
	N=297	N=117	OR (95% CI)	P value	OR (95% CI)	P value
Sex, n (column %)						
Male	284 (95.6)	117 (100)	Ref			
Female	13 (4.4)	0 (0.0)	---	0.024	---	
Age (years), median (P25–P75)	36.1 (28.9–45.1)	42.1 (34.8–49.7)	1.04 (1.02 to 1.06)	<0.001	1.04 (1.01 to 1.06)	0.001
BMI (kg/m^2)†, mean (SD)	28.2 (5.8)	26.5 (4.5)	0.94 (0.90 to 0.98)	0.007	0.94 (0.90 to 0.99)	0.012
Smoking history, n (column %)						
Never	126 (42.4)	29 (24.8)	Ref		Ref	
Former/current	171 (57.6)	88 (75.2)	2.24 (1.39 to 3.61)	0.001	2.17 (1.32 to 3.56)	0.002
Pack years†, median (P25–P75)						
All	0.4 (0.0–7.1)	7.5 (0.0–13.8)	1.07 (1.04 to 1.09)	<0.001	1.07 (1.04 to 1.10)	<0.001
Former/current smokers only	6.5 (2.4–11.4)	11.0 (6.1–20.2)	1.06 (1.03 to 1.09)	<0.001	1.06 (1.02 to 1.10)	0.004
Country of birth, n (column %)						
Australia	164 (56.5)	48 (42.1)	Ref		Ref	
Other (not Australia)	126 (43.5)	66 (57.9)	1.79 (1.15 to 2.77)	0.009	1.37 (0.86 to 2.20)	0.190
Rose dyspnoea score, n (column %)						
0	208 (70.3)	71 (60.7)	Ref		Ref	
1	62 (20.1)	22 (18.8)	1.04 (0.60 to 1.81)	0.891	1.15 (0.63 to 2.09)	0.643
2	18 (6.1)	12 (10.3)	1.95 (0.90 to 4.25)	0.092	2.65 (1.10 to 6.38)	0.030
3	8 (2.7)	12 (10.3)	4.39 (1.73 to 11.19)	0.002	4.69 (1.60 to 13.78)	0.005
SBI exposures						
SBI career duration, years						
Median (P25–P75)	8 (5–14)	12 (9–21)	1.07 (1.04 to 1.09)	<0.001	1.08 (1.04 to 1.12)	<0.001
Range	<1–44	3–43				
Age at first SBI job, years						
Median (P25–P75)	25 (20–33)	25 (20–33)	1.00 (0.98 to 1.03)	0.923	0.99 (0.96 to 1.01)	0.289
Range	15–59	13–58				
No of SBI jobs held, n						
Median (P25–P75)	2 (1–3)	3 (2–4)	1.32 (1.17 to 1.48)	<0.001	1.19 (1.04 to 1.37)	0.014
Range	1–9	1–30				
Highest dry processing exposure intensity from both personal and bystander exposure, n (column %)						
Never	15 (5.1)	2 (1.7)	Ref		Ref	
Rarely 1%–9%	19 (6.4)	4 (3.4)	1.58 (0.25 to 9.82)	0.624	1.24 (0.18 to 8.47)	0.827
Sometimes 10%–24%	41 (13.8)	14 (12.0)	2.56 (0.52 to 12.62)	0.248	2.59 (0.49 to 13.65)	0.261
Frequently 25%–49%	53 (17.8)	13 (11.1)	1.84 (0.37 to 9.07)	0.454	1.63 (0.31 to 8.65)	0.565
Very frequently 50%–99%	101 (34.0)	43 (36.7)	3.19 (0.70 to 14.57)	0.134	2.94 (0.60 to 14.32)	0.183
Always 100%	68 (22.9)	41 (35.1)	4.52 (0.98 to 20.79)	0.053	3.89 (0.78 to 19.38)	0.097
Estimated silica exposure category, n (column %)						
Low/medium	40 (13.5)	5 (4.3)	Ref		Ref	
High/very high	257 (86.5)	112 (95.7)	3.49 (1.34 to 9.07)	0.010	4.46 (1.65 to 12.07)	0.003

*Factors adjusted for include age, BMI, smoking status and country of birth. Age and BMI were highly correlated therefore BMI centred at the mean was used in the regression models. Age at first exposure was highly correlated with age, therefore, in the adjusted model assessing the relationship between age at first SBI job and silicosis diagnosis, age was excluded. Highest exposure was additionally adjusted for career duration. Number of SBI jobs held was additionally adjusted for career duration.
†BMI data missing for 5; number of cigarettes missing for 46.
BMI, body mass index; col, column; P25, 25th percentile; P75, 75th percentile; SBI, stone benchtop industry.

work time. Twenty-six (4.8%) worked only with artificial stone and 25 (4.6%) only with natural stone.

Exposure to dry processing of stone was very common. Most (70%) indicated that they had worked in at least one job where they had personal and/or bystander exposure for at least 10% of their time at that workplace, and 46.5% for at least 50% of their work time. Only 70 workers (13.8%) never had personal or bystander exposure to dry processing. Two-thirds (67.8%) of the cohort were categorised as having 'high' or 'very high' estimated silica exposure.

Screening outcomes

In accordance with the screening programme's methodology, 130 workers (23.9%) assessed in primary screening were not determined to be at high risk and did not undergo secondary screening.[16] The remaining 414 (76.1%) workers, fulfilled the following prespecified criteria to require secondary screening: 'high' or 'very high' estimated silica exposure (89.1%); significant symptoms or signs (64.7%); CXR ILO profusion category≥1 (27.5%) and/or prebronchodilator respiratory function parameter(s) below the LLN (FEV_1 10.0%, FVC 7.6%, FEV_1/

Table 4 Relationship between silicosis diagnosis (outcome measure) and respiratory function tests for secondary screening participants

	No silicosis	Confirmed silicosis	No silicosis (ref) versus confirmed silicosis*	Simple silicosis	Complicated silicosis	Simple (ref) versus complicated silicosis
	N=297	N=117	OR (95% CI)	N=96	N=21	OR (95% CI)
FEV_1†						
Percentage of predicted, mean(SD)	98.0 (14.4)	93.3 (18.0)	0.98 (0.96 to 0.99)	95.9 (16.9)	81.1 (18.4)	0.96 (0.93 to 0.99)
z-score, median (P25, P75)	−0.2 (−0.8, 0.6)	−0.3 (−1.3, 0.5)	0.77 (0.63 to 0.95)	−0.1 (−0.9,0.5)	−1.7 (−2.3,−0.2)	0.56 (0.36 to 0.87)
FVC†						
Percentage of predicted, mean (SD)	101.9 (13.2)	98.3 (16.0)	0.98 (0.96 to 1.00)	100.6 (14.4)	87.5 (19.2)	0.95 (0.91 to 0.99)
z-score, median (P25, P75)	0.3 (−0.6, 0.8)	0.0 (−0.9, 0.7)	0.79 (0.64 to 0.98)	0.2 (−0.7,0.8)	−1.2 (−2.1,−0.1)	0.52 (0.32 to 0.84)
FEV_1/FVC†						
Percentage of predicted, mean (SD)	95.9 (7.8)	94.7 (10.9)	0.98 (0.95 to 1.01)	95.1 (11.1)	92.8 (9.9)	0.99 (0.94 to 1.04)
z-score, median (P25, P75)	−0.4 (−1.1, 0.1)	−0.7 (−1.5,0.3)	0.88 (0.70 to 1.10)	−0.5 (−1.6,0.3)	−1.1 (−1.5,−0.3)	0.88 (0.59 to 1.33)
$D_L$co†						
Percentage of predicted, mean (SD)	104.2 (17.9)	94.9 (19.4)	0.98 (0.97 to 0.99)	99.0 (16.3)	76.0 (21.8)	0.92 (0.87 to 0.96)
z-score, median (P25, P75)	0.3 (−0.5, 1.0)	−0.4 (−1.2,0.4)	0.75 (0.62 to 0.93)	−0.3 (−1.0,0.5)	−2.1 (−2.6,−0.4)	0.31 (0.16 to 0.59)
Reduced $D_L$co (<LLN), n (column %)						
No	229 (93.8)	83 (86.5)	Ref	77 (97.5)	6 (35.3)	Ref
Yes	15 (6.2)	13 (13.5)	1.80 (0.78 to 4.15)	2 (2.5)	11 (64.7)	76.6 (10.7 to 546.14)
Respiratory function patterns‡, n (column %)						
Normal	206 (84.4)	65 (67.7)	Ref	57 (72.1)	8 (47.1)	Ref
Restrictive	10 (4.1)	11 (11.5)	3.03 (1.13 to 8.12)	4 (5.1)	7 (41.2)	13.18 (2.64 to 65.86)
Obstructive	26 (10.7)	17 (17.7)	2.29 (1.10 to 4.77)	15 (19.0)	2 (11.7)	0.87 (0.15 to 4.97)
Mixed	2 (0.8)	3 (1.2)	5.43 (0.83 to 35.6)	3 (3.8)	0 (0)	–

*RFT data missing for 74 patients.
†Normal=FEV_1/FVC ratio ≥LLN and FVC≥LLN; Restrictive=FEV_1/FVC ratio ≥LLN and FVC<LLN; obstructive=FEV_1/FVC ratio <LLN and FVC≥LLN; mixed=FEV_1/FVC ratio <LLN and FVC<LLN.[19]
‡Adjusted for age, BMI, smoking and country of birth. FEV1, FVC, FEV1/FVC and DLco not adjusted for age.
BMI, body mass index; DLco, diffusion capacity for carbon monoxide; FEV1, forced expiratory volume in 1 s; FVC, forced vital capacity; LLN, lower limit of normal.

FVC ratio 14.1%, DLCO 8.2%) (online supplemental e-Tables 2 and 3).

Given that the 130 workers who underwent primary screening only did not have an HRCT chest performed, they will not be considered further in this report. Secondary screening participants had a median SBI career duration of 10 years (range <1–44 years), and 11% had an estimated low or medium silica exposure level.

Among the 414 participants who met the prespecified criteria for secondary screening, the prevalence of silicosis was 28.3% (n=117; 95% CI 24.0 to 32.9). There were 96 with simple and 21 with complicated silicosis. The relationship between participant characteristics and silicosis prevalence is presented in table 3. There were no female cases diagnosed. Men with silicosis were significantly older, with a median age of 42.1 compared with 36.1 years among men without a silicosis diagnosis. Smoking history was significantly associated with silicosis. BMI was lower in those with silicosis compared with those without (26.5 kg/m^2 vs 28.2 kg/m^2). There was a non-significant elevated risk of complicated compared with simple silicosis for current and former smokers compared with non-smokers (OR 3.72 (95% CI 0.81 to 17.06), and higher levels of maximum personal or secondary exposure to dry processing of stone (OR 4.94 (95% CI 0.62 to 39.12) (online supplemental e-Table 4).

Participants with silicosis had a longer duration of work in the SBI (median 12 years compared with 8 years) and higher median number of jobs held (3 jobs compared with 2). Thirty per cent of workers assigned a 'high' or 'very high' silica exposure had silicosis compared with 11.1% of among those assigned 'low' or 'medium' exposure (table 2). Only 2/117 of workers diagnosed with silicosis indicated that they never worked in a job with either personal or bystander exposure to dry processing of stone.

Predictive value of RFTs and CXR in secondary screening participants

A diagnosis of silicosis was associated with worse spirometry and $D_L$co (table 4). The most common abnormal spirometric pattern was obstructive among those with simple silicosis and restrictive for those with complicated silicosis. Mean FEV_1, FVC and $D_L$co were significantly lower among those with complicated silicosis compared with simple silicosis. The mean $D_L$co in those with complicated silicosis was, however, the only RFT parameter below 80% of predicted. Thirty-six workers with an ILO category 0 CXR had a diagnosis of silicosis from HRCT chest and respiratory physician assessment, all had simple silicosis (36/91, 39.6%). All workers with complicated silicosis had an ILO category CXR of ≥1.

In participants who underwent secondary screening, using the HRCT and respiratory physician assessment as the 'gold standard' for diagnosis of silicosis, RFTs and CXRs were assessed as screening tools (table 5). All RFT parameters had poor sensitivity for silicosis. The parameter with the highest positive predictive value (PPV) for the diagnosis was FVC (53.8%).

In the population that underwent secondary screening, an ILO small opacity profusion category of ≥1 was associated with sensitivity 66.7%, specificity 86.9%, negative predictive value 87.7% and PPV 64.9%, for a diagnosis of silicosis.

Table 5 Predictive values of ILO chest X-ray and respiratory function parameters for identifying silicosis when compared with respiratory physician assessments with HRCT for secondary screening participants

	No silicosis from secondary screening	Silicosis from secondary screening	Sensitivity % (95% CI)	Specificity % (95% CI)	NPV% (95% CI)	PPV% (95% CI)	LR+ (95% CI)	LR− (95% CI)
Chest X-ray								
ILO profusion category 0	246	36	67.3 (57.7 to 75.9)	86.0 (81.4 to 89.8)	87.2 (82.8 to 90.9)	64.9 (55.4 to 73.6)	4.81 (3.51 to 6.59)	0.38 (0.29 to 0.50)
ILO profusion category ≥1	40	74						
Respiratory function parameter								
FEV_1								
≥ LLN	228	78	18.8 (11.5 to 28.0)	93.4 (89.6 to 96.2)	74.5 (69.2 to 79.3)	52.9 (35.1 to 70.2)	2.86 (1.52 to 5.37)	0.87 (0.79 to 0.96)
<LLN	16	18						
FVC								
≥ LLN	232	82	14.6 (8.2 to 23.3)	95.1 (91.6 to 97.4)	73.9 (68.7 to 78.7)	53.8 (33.4 to 73.4)	2.97 (1.42 to 6.18)	0.90 (0.82 to 0.98)
<LLN	12	14						
FEV_1/FVC								
≥ LLN	216	76	20.8 (13.2 to 30.3)	88.5 (83.8 to 92.2)	74.0 (68.5 to 78.9)	41.7 (27.6 to 56.8)	1.82 (1.08 to 3.06)	0.89 (0.80 to 1.00)
<LLN	28	20						
D_Lco								
≥ LLN	229	83	13.5 (7.4 to 22.0)	93.9 (90.1 to 96.5)	73.4 (68.1 to 78.2)	46.4 (27.5 to 66.1)	2.20 (1.09 to 4.45)	0.92 (0.85 to 1.00)
<LLN	15	13						

FEV1, forced expiratory volume in 1 s; FVC, forced vital capacity; HRCT, high-resolution CT; ILO, International Labour Office; LLN, lower limit of normal; LR, likelihood ratio; NPV, negative predictive value; PPV, positive predictive value.

DISCUSSION

In this large cohort of 414 high-risk SBI workers who underwent detailed screening, including HRCT chest imaging, 28.3% were diagnosed with silicosis. This study confirmed a very high risk of silicosis associated with work in the SBI. This prevalence estimate is similar to that found in another screening programme undertaken in Queensland, Australia. That WHS regulator identified 240 (22.7%) participants with silicosis, including 36 with progressive massive fibrosis.[22]

Our study showed that the use of artificial stone and the practice of dry processing stone have been extremely common in the SBI and are both major factors in many of the cases diagnosed.[18] Dry processing of artificial stone with high intensity power tools has been found to generate very high RCS levels.[11 12] A study of four benchtop fabrication businesses in the United States found that the exposure of all workers who used dry methods, even for a very limited time, exceeded the full-shift time-weighted average (TWA) exposure American Conference of Governmental Industrial Hygienists threshold limit value (TLV) of 0.025 mg/m^3.[11] TWA RCS levels of up to 3.88 mg/m^3 were measured, 155 times the TLV.[11] An experimental study reported even higher exposure to RCS generated when cutting artificial stone with a circular saw without use of engineering controls.[12] Dry processing of artificial stone is a highly hazardous work practice that has been reported in association with silicosis from many countries.[4 7]

Half the SBI cohort were current or former smokers. As has been shown in other studies, the risk of silicosis was significantly associated with smoking.[23] RCS exposure has been classified as carcinogenic by IARC since 1997, and more recent evidence has indicated that smoking substantially increases the risk of lung cancer in RCS exposed workers.[24 25] Clearly, smoking cessation support is an important intervention for these workers.

More than half of those with silicosis in our cohort had migrated to Australia. Migrant workers have been recognised to be at increased risk of occupational disease. A literature review of 12 168 international migrant workers employed in 13 countries noted a 47% prevalence of occupational morbidity.[26] The high proportion of migrant workers in our study demonstrates the need to ensure that culturally and linguistically appropriate occupational health and safety training is provided. Further research is urgently required to understand the potential vulnerabilities of migrant workers in the SBI and potential barriers to prevention such as precarious employment.

In our cohort, the median duration of time from first silica exposure to silicosis diagnosis was 12 years, which is substantially shorter than the typical latency of silicosis associated with natural sources of silica, such as those found in mining.[27] The exposure duration was also shorter than reported in cohorts of workers with artificial stone silicosis from Israel (21.3 years) and USA (17.3 years), but comparable with those reported in other regions that have instituted active screening including Queensland (10.6 years) and Spain (12 years).[4 6] This suggests that active screening can detect disease earlier, with potential benefits in terms of limiting subsequent exposure and reducing the risk of severe disease. Most workers with silicosis in our cohort did not experience any dyspnoea with physical activity, therefore, symptoms should not be used as a marker of possible disease.

Internationally, CXR with ILO classification and spirometry are the basis of pneumoconiosis surveillance programmes. Our results demonstrated poor sensitivity and PPV for these tests for high-risk SBI workers that met the programme criteria for secondary screening, when compared with an assessment with an HRCT chest and respiratory physician. Over one-third of participants with simple silicosis were reported to have a normal (ILO profusion category 0) CXR and would not have been detected without performing an HRCT. These results reinforce that a normal CXR cannot exclude silicosis, especially early stage disease.[15 28]

Further consideration of the use of CT imaging for the screening of silica exposed workers is required, especially in the SBI. The higher sensitivity of CT to detect early disease must be weighed against the higher radiation exposure, cost and need for periodic retesting of workers. Potentially new technologies such as ultra-low-dose CT imaging or artificial intelligence tools applied to chest radiography may play an important role.

Ongoing health monitoring is important for workers who have been exposed to hazardous levels of silica but where screening has not yet detected disease. Seventy percent of workers in our study who had a 'high' or 'very high' estimated RCS exposure did not have a diagnosis of silicosis. The latency period between RCS exposure and development of silicosis can be over two decades, therefore, workers will remain at risk of developing silicosis and other silica-associated diseases for many years.[29] Concerningly, during 4 years follow-up of denim jeans sandblasters who had previously been exposed to high levels of RCS, the prevalence of silicosis increased from 55% to 96%.[30]

This study had several strengths. This is the largest reported cohort of SBI workers to have undergone comprehensive, protocolised screening assessments. Although participation was voluntary, the cohort was a substantial proportion of the 1400 workers estimated to be in the industry by the Victorian Government in 2019.[31] Even though the 414 participants who underwent secondary screening, including HRCT, were required to meet a priori risk criteria, we believe this cohort was representative of a large proportion of the industry in Victoria at the time of the study. Seventy-six per cent of participants met the criteria for secondary screening and this included 11% with 'low' or 'moderate' estimated levels of RCS exposure. Of note, six participants who had 'low' or 'medium' estimated levels of exposure were diagnosed with silicosis. This suggests that the risk of silicosis in the SBI also includes those with a lower level of exposure.

The study also had some limitations. In this real-world study, chest imaging was only read by a single radiologist and severity of silicosis on HRCT was limited to definitions of simple and complicated silicosis, rather than use of a grading system such as the complex International Classification of High-resolution Computed Tomography for Occupational and Environmental Respiratory Diseases.[32] Additionally, the reported 28% silicosis prevalence could be an overestimation if applied to the entire SBI for two reasons. First, participation in screening and the study was voluntary, and potentially workers who perceived themselves to have experienced more hazardous work environments could have been more likely to participate. Second, to minimise radiation exposure, 130 workers considered (prior to the commencement of the study) to be at low risk of silicosis underwent primary screening only, without an HRCT. Because a diagnosis of silicosis could not be completely discounted in this group, they were excluded from the prevalence estimate, potentially skewing the estimate to a higher-risk group of SBI workers. Conversely, however, recruitment for the programme focused on actively employed SBI workers, therefore, the 'healthy worker effect' may have influenced participation and have led to an underestimation of prevalence of silicosis.[33]

It is also important to note that estimated RCS exposure levels were based on participants' questionnaire responses rather than workplace samples, which were not available. This methodology may be subject to both over-reporting and under-reporting of perceived exposure by participants. Questionnaire responses, however, indicated that at the time of the study, the highly hazardous practice of dry processing of stone was alarmingly common.

Our findings have implications worldwide. There has been rapid growth in the popularity of artificial stone globally. Despite this, there are no current data indicating how many people work in this industry, nor is there information about the pervasiveness of the practice of dry processing of stone. Given the prevalence of silicosis reported here and in Queensland, there is the potential for a major public health crisis. In the USA, where importation of artificial stone increased by 800% between 2010 and 2018, there were estimated to be almost 100 000 workers in the industry.[7] Taking into account that our study reported silicosis prevalence in a potentially higher-risk population, use of a more conservative estimate of disease prevalence of 20% would equate to 20 000 cases of silicosis in that country alone.[7]

CONCLUSION

This study demonstrated a high prevalence of silicosis, a preventable occupational lung disease, among workers in the SBI. Active screening can detect more cases earlier, with a greater potential to prevent more serious disease developing. Relying on symptoms or screening with RFTs or CXR will miss many cases, suggesting that HRCT is required. Internationally, thousands of workers are at risk of silicosis and other silica associated diseases. Urgent action is required to identify affected workers and provide them with appropriate management. Implementation of effective hazard control measures to protect workers in this industry are well overdue and should include the elimination of very high silica content artificial stone or at the very least, cessation of dry processing.

Twitter Karen Walker-Bone @kwb_doc

Contributors RFH is the content guarantor. RFH had full access to all of the data in the study and took responsibility for the integrity of the data and the accuracy of the data analysis. CD, MA, DCG, SMG, FH-L, JJ-M, KW-B and MRS contributed substantially to the study design, data analysis and interpretation, and the writing of the manuscript.

Funding This work was supported by WorkSafe Victoria. Award number: not applicable.

Competing interests MA holds investigator initiated grants from Pfizer, Boehringer-Ingelheim, Sanofi and GSK for unrelated research. He has also undertaken an unrelated consultancy for Sanofi and received a speaker's fee from GSK.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants and was approved by Monash University, project number 17730. Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement No data are available.

ORCID iDs
Ryan F Hoy http://orcid.org/0000-0001-9150-9440
Deborah C Glass http://orcid.org/0000-0002-7559-008X
StellaMay Gwini http://orcid.org/0000-0002-0295-4575
Karen Walker-Bone http://orcid.org/0000-0002-5992-1459
Malcolm R Sim http://orcid.org/0000-0003-4739-2817

REFERENCES

1 Frankel A, Blake L, Yates D. Complicated silicosis in an Australian worker from cutting engineered stone countertops: an embarrassing first for Australia. *Eur Respir J* 2015;46:PA1144.
2 Hoy RF, Sim MR. Correspondence on 'demographic, exposure and clinical characteristics in a multinational Registry of engineered stone workers with Silicosis' by Hua *et Al*. *Occup Environ Med* 2022;79:647–8.
3 Hoy RF, Baird T, Hammerschlag G, *et al*. Artificial stone-associated silicosis: a rapidly emerging occupational lung disease. *Occup Environ Med* 2018;75:3–5.
4 León-Jiménez A, Hidalgo-Molina A, Conde-Sánchez MÁ, *et al*. Artificial stone silicosis: rapid progression following exposure cessation. *Chest* 2020;158:1060–8.
5 Wu N, Xue C, Yu S, *et al*. Artificial stone-associated silicosis in China: a prospective comparison with natural stone-associated silicosis. *Respirology* 2020;25:518–24.
6 Hua JT, Zell-Baran L, Go LHT, *et al*. Demographic, exposure and clinical characteristics in a multinational registry of engineered stone workers with silicosis. *Occup Environ Med* 2022;79:849–50.
7 Rose C, Heinzerling A, Patel K, *et al*. Severe silicosis in engineered stone fabrication workers - California, Colorado, Texas, and Washington, 2017-2019. *MMWR Morb Mortal Wkly Rep* 2019;68:813–8.
8 Levin K, McLean C, Hoy R. Artificial stone-associated silicosis: clinical-pathological-radiological correlates of disease. *Respirol Case Rep* 2019;7:e00470.
9 Kumarasamy C, Pisaniello D, Gaskin S, *et al*. What do safety data sheets for artificial stone products tell us about composition? A comparative analysis with physicochemical data. *Ann Work Expo Health* 2022;66:937–45.
10 Mandler WK, Qi C, Qian Y. Hazardous dusts from the fabrication of countertop: a review. *Arch Environ Occup Health* 2023;78:118–26.
11 Phillips ML, Johnson DL, Johnson AC. Determinants of respirable silica exposure in stone countertop fabrication: a preliminary study. *J Occup Environ Hyg* 2013;10:368–73.
12 Cooper JH, Johnson DL, Phillips ML. Respirable silica dust suppression during artificial stone countertop cutting. *Ann Occup Hyg* 2015;59:122–6.
13 Maharjan P, Crea J, Tkaczuk M, *et al*. Metal ion release from engineered stone dust in artificial lysosomal fluid-variation with time and stone type. *Int J Environ Res Public Health* 2021;18:6391.
14 Carrieri M, Guzzardo C, Farcas D, *et al*. Characterization of silica exposure during manufacturing of artificial stone countertops. *IJERPH* 2020;17:4489.
15 Newbigin K, Parsons R, Deller D, *et al*. Stonemasons with silicosis: preliminary findings and a warning message from Australia. *Respirology* 2019;24:1220–1.
16 Hoy RF, Glass DC, Dimitriadis C, *et al*. Identification of early-stage silicosis through health screening of stone benchtop industry workers in Victoria, Australia. *Occup Environ Med* 2021;78:296–302.
17 Hoy RF, Hansen J, Glass DC, *et al*. Serum angiotensin converting enzyme elevation in association with artificial stone silicosis. *Respir Med* 2020;177:106289.
18 Glass DC, Dimitriadis C, Hansen J, *et al*. Silica exposure estimates in artificial stone benchtop fabrication and adverse respiratory outcomes. *Ann Work Expo Health* 2022;66:5–13.
19 Pellegrino R, Viegi G, Brusasco V, *et al*. Interpretative strategies for lung function tests. *Eur Respir J* 2005;26:948–68.
20 Harris PA, Taylor R, Minor BL, *et al*. The REDcap consortium: building an international community of software platform partners. *J Biomed Inform* 2019;95:103208.
21 Rose GA, Blackburn H. Cardiovascular survey methods. *Monogr Ser World Health Organ* 1968;56:1–188.
22 WorkSafe Queensland. Silicosis - Workcover Screening Outcomes. 2022. Available: https://www.worksafe.qld.gov.au/claims-and-insurance/work-related-injuries/types-of-injury-or-illness/work-related-respiratory-diseases/silicosis [Accessed 11 Nov 2022].
23 Poinen-Rughooputh S, Rughooputh MS, Guo Y, *et al*. Sex-related differences in the risk of silicosis among Chinese pottery workers: a cohort study. *J Occup Environ Med* 2021;63:74–9.
24 International Agency for Research on Cancer. Silica dust, crystalline, in the form of quartz or Cristobalite. In: *Arsenic, metals, fibres and dusts*. Lyon (FR): International Agency for Research on Cancer, 2018.
25 Liu Y, Steenland K, Rong Y, *et al*. Exposure-response analysis and risk assessment for lung cancer in relationship to silica exposure: a 44-year cohort study of 34,018 workers. *Am J Epidemiol* 2013;178:1424–33.
26 Hargreaves S, Rustage K, Nellums LB, *et al*. Occupational health outcomes among international migrant workers: a systematic review and meta-analysis. *Lancet Glob Health* 2019;7:e872–82.
27 Haibing Y, Lei Y, Junyue Z, *et al*. Natural course of silicosis in dust-exposed workers. *J Huazhong Univ Sci Technol [Med Sci]* 2006;26:257–60.
28 Meijer E, Tjoe Nij E, Kraus T, *et al*. Pneumoconiosis and emphysema in construction workers: results of HRCT and lung function findings. *Occup Environ Med* 2011;68:542–6.
29 Shtraichman O, Blanc PD, Ollech JE, *et al*. Outbreak of autoimmune disease in silicosis linked to artificial stone. *Occup Med (Lond)* 2015;65:444–50.
30 Akgun M, Araz O, Ucar EY, *et al*. Silicosis appears inevitable among former denim sandblasters. *CHEST* 2015;148:647–54.
31 Victorian Government. Regulations banning dry stone cutting now in effect. 2019. Available: https://www.premier.vic.gov.au/regulations-banning-dry-stone-cutting-now-effect [Accessed 25 Jan 2023].
32 Suganuma N, Kusaka Y, Hering KG, *et al*. Reliability of the proposed international classification of high-resolution computed tomography for occupational and environmental respiratory diseases. *J Occup Health* 2009;51:210–22.
33 Chowdhury R, Shah D, Payal AR. Healthy worker effect phenomenon: Revisited with emphasis on statistical methods - A review. *Indian J Occup Environ Med* 2017;21:2–8.