Evaluation of workplace exposure to respirable crystalline silica in Italy

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Background: Crystalline silica is a human carcinogen and its use is widespread among construction, mining, foundries, and other manufacturing industries.

Purpose: To evaluate occupational exposure to crystalline silica in Italy.

Methods: Data were collected from exposure registries and descriptive statistics were calculated for exposure-related variables. The number of potentially exposed workers was estimated in a subset of industrial sectors. Linear mixed model analysis was performed to determine factors affecting the exposure level.

Results: We found 1387 cases of crystalline silica exposure between 1996 and 2012. Exposure was most common in construction work ($AM=0.057 \text{ mg/m}^3$, $N=505$), and among miners and quarry workers ($AM=0.048 \text{ mg/m}^3$, $N=238$). We estimated that 41 643 workers were at risk of exposure in the selected industrial sectors during the same period.

Conclusions: This study identified high-risk sectors for occupational exposure to crystalline silica, which can help guide targeted dust control interventions and health promotion campaigns in the workplace.

Keywords: Exposure assessment, Crystalline silica, Occupational health, Inhalation, Italy

Introduction

Human exposure to respirable crystalline silica (RCS), primarily quartz dust, occurs in a variety of industrial and occupational settings including: quarry and mining, mineral processing, foundry, construction, ceramic, and brick and tile industries.¹

The International Agency for Research on Cancer classified crystalline silicas (including quartz, cristobalite, tridymite, and tripoli) as known human carcinogens.² Recently, 28 712 workers in Italy were estimated to potentially be at high risk of silica exposure, a figure based on compensated cases for silicosis between 2000 and 2004.³ The European study CAREX (CARcinogen EXposure) estimated 254 657 workers were exposed to crystalline silica in Italy, based on figures of exposed Finnish and North American workers, adapted to the Italian industry.⁴ According to the same study, over 3.2 million workers in the European Union have been exposed to crystalline silica.⁵

The health risks associated with silica dust increase with the quantity and duration of exposure. In 2007, the American Conference of Governmental Industrial Hygienists (ACGIH) lowered the 8-hour working exposure limit (TLV–TWA) for crystalline silica from

0.05 to 0.025 mg/m^3 .⁶ In Europe, the Scientific Committee on Occupational Exposure Limits (SCOEL) recommends that exposure to RCS dust be kept below 0.05 mg/m^3 for a full 8-hour shift.⁷ The adoption of a binding occupational exposure limit value by the European Union is under discussion and is proposed for inclusion in the next revision of the Directive 2004/37EC on the protection of workers from the risks of exposure to carcinogens and mutagens at work.

Since 1996, the SIREP (Information System for Recording Occupational Exposures to Carcinogens, Italian acronym) database has been used to record the number of workers exposed to carcinogens and their exposure levels in the workplace. The purpose of this study is to estimate the total number of workers potentially exposed to RCS and to describe the level of occupational exposure to RCS in Italy between the years 1996–2012.

Methods

Data gathering

The SIREP system has been fully described elsewhere.⁸ In brief, Italian law requires that employers collect exposure data for select carcinogens and report to SIREP every 3 years. Reporting is mandatory for carcinogens classified as 1 and 2 by the European Union (1, substance known to be carcinogenic to

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humans; 2, substances that should be regarded as if carcinogenic to humans), but is voluntary for other possibly carcinogenic substances, including silica. Employers are required to report carcinogen type, anagraphical and occupational data of exposed employees, and exposure levels. The information reported by employers is standardized and includes: the firm's economic activity sector and work force size; workers' personal data and job type; year of measurement and level of exposure (magnitude, frequency, and duration). Employers are responsible for the measurement procedures and air sampling methods in accordance with European standards, which provide technical guidance to implement a dust monitoring strategy.⁹

Data selection

A total of 1387 RCS measurements, representing 1341 exposures (1115 workers in 144 different firms) between 1996 and 2012 were selected from the SIREP database for analysis (313 exposures were excluded from analysis as the measurement was not specified). The airborne concentration of RCS for some exposures ($N=44$) was measured at least twice between 1996 and 2012. The crystalline silica forms studied included quartz, cristobalite, tridymite, and tripoli. Measurements ($N=470$) that were below the analytical limit of detection (LOD) were replaced with the LOD value divided by two (LOD/2).¹⁰ Air sampling measurements were collected over an eight hour work shift. Information on the type of sampling methodology (personal or stationary) was not available. In order to increase the precision of the estimates, only sectors and occupations having more than 50 measurements were included in the descriptive analysis. International standard classifications were used to code economic activity sectors of firms (NACE Rev. 1) and worker occupation (ISCO-88). Descriptive statistical analyses were used to calculate the means (arithmetic and geometric) of RCS exposure levels in addition to 95% confidence intervals (CI), standard deviations (SD), and geometric standard deviations (GSD).

Estimating exposed workers

Owing to the shortage of data available about certain industrial sectors, the number of workers potentially exposed to RCS was estimated only for the sectors for which the percentage of reported work force (exposed together with non-exposed) was more than 1% of the total sector work force ($RW_i/W_i > 1\%$, where RW_i is the SIREP reported work force, W_i is the total work force, and i is the i th economic sector), and with at least three firms recorded. The total sector work force was estimated using national statistics from the Italian Institute for Statistics (ISTAT).¹¹ For included industrial sectors, the number of potentially RCS exposed workers was reconstructed using the percentage of

exposed workers in relation to both the work force size of firms recorded in SIREP and the national statistics on work force (i.e. $PE_i = W_i \times (E_i/RW_i)$, where PE_i is the potentially exposed workers, W_i is the ISTAT total work force, RW_i is the SIREP reported work force, and E_i is the SIREP exposed workers). SIREP exposed workers (E_i) is the total number of workers with RCS exposure measurements recorded in SIREP (including those with levels below the LOD), for the i th economic sector. Results were stratified by gender.

Mixed-effects model

A mixed effects model with a random firm-specific intercept was adopted to evaluate the association between exposure variables and air RCS concentration. A non-parametric one-way analysis of variance using the Kruskal–Wallis test was applied to detect and identify variables influencing the exposure level and only variables statistically significant at the $P < 0.05$ were included in the model. All independent variables (fixed effects) in the model were categorical: RCS form (quartz, cristobalite, tripoli), economic sector (NACE codes), firm size (<10 workers, $10-20$ workers, $20-50$ workers, $50-100$ workers, ≥ 100 workers), firm location (by Italian region), occupation (ISCO-88 codes), and year. Exposure measurements were natural log transformed to account for positively skewed data and approximately log-normal distributed. A restricted maximum likelihood estimation method was used in the mixed model and the Akaike Information Criterion was applied to achieve the best fitting model.

The mixed-effects model is described by the following equation:

$$\ln(Y_i) = \sum(\text{Fixed effects}) + (\text{Firm effect})_i + (\text{Error})_i$$

for $i=1, 2, \dots, n$ (firms), where Y_i is the exposure level. The model assumptions are: random effect corresponding to firm (Firm effect) is approximately normally distributed with a mean of 0 and a variance of σ_B^2 ; residual (Error) is approximately normally distributed with a mean of 0 and a variance of σ_W^2 ; and (Firm effect) and (Error) are statistically independent.

Partial eta squared (η^2) was computed for each specific effect to measure the degree of association using F -test statistics and the following formula:

$$\eta^2 = F_{\text{effect}}(DF_{\text{effect}}) / F_{\text{effect}}(DF_{\text{effect}}) + DF_{\text{error}}$$

The data were analyzed with SAS statistical software version 9.3 (MIXED procedure; SAS Institute, Inc., Cary, NC, USA). This study is part of a research project with the Italian Workers' Compensation Authority in the institutional research plan for the years 2013–2015 (code P01L02).

Table 1 Descriptive statistics of RCS exposure by economic activity sector (male only; SIREP, 1996–2012).

Economic activity sector (NACE code)	N	NH	AM	GM	GSD	(95% CI)
Manufacture of other non-metallic mineral products (26)	315	49	0.053	0.017	4.203	0.015–0.020
Manufacture of basic metals (27)	181	21	0.013	0.007	2.617	0.006–0.008
Manufacture of furniture; manufacturing n.e.c. (36)	217	39	0.037	0.010	4.315	0.008–0.012
Construction (45)	505	471	0.057	0.045	1.707	0.043–0.047
Other sectors	132	33	–	–	–	–

Note: N: number of 8-hour TWA exposure measurements (mg/m³); NH: number of 8-hour TWA exposure measurements (mg/m³) exceeding the limit proposed by ACGIH; AM: arithmetic mean; GM: geometric mean; GSD: geometric standard deviation; CI: confidence interval; n.e.c.: not elsewhere classified.

Only sectors with at least 50 exposure measurements are shown.

Results

Descriptive statistics

The mean airborne concentration of RCS in workplaces was slightly higher for men ($N=1350$, $AM=0.05$ mg/m³, $SD=0.14$, $GM=0.018$ mg/m³, $GSD=4.51$, 95% $CI=0.017–0.019$) than for women ($N=37$, $AM=0.05$ mg/m³, $SD=0.14$, $GM=0.009$ mg/m³, $GSD=5.67$, 95% $CI=0.005–0.015$). Since the female group had few exposure measurements, no further analysis was performed. The greatest number of measurements occurred in the construction sector ($N=505$ men, $GM=0.045$ mg/m³, $GSD=1.71$), and the lowest level of exposure was in the manufacturing of basic metals sector ($N=181$ men, $GM=0.007$ mg/m³, $GSD=2.62$). The highest percentage of measurements exceeding the exposure limit proposed by ACGIH was in the construction sector (93%) and for miners and quarry workers (97%). Overall, 44% of exposed workers had an exposure measurement equal to or above the limit recommended by SCOEL (0.05 mg/m³), while 50% had a value exceeding that proposed by ACGIH (0.025 mg/m³). Distribution by industrial sector is shown in Table 1 and distribution by occupational group is provided in Table 2.

Among RCS forms, the GM concentration was the highest for the cristobalite ($N=644$, $GM=0.025$ mg/m³, $GSD=3.92$), and similar for quartz ($N=589$, $GM=0.013$ mg/m³, $GSD=4.71$) and tripoli ($N=96$, $GM=0.012$ mg/m³, $GSD=2.02$).

Regarding the distribution of RCS exposure level by work force size, micro and small firms (<10–20 employees) had the lowest exposure risk ($N=184$,

$GM=0.007$ mg/m³, 95% $CI=0.005–0.009$), whereas the highest exposure ($N=553$, $GM=0.032$, 95% $CI=0.029–0.034$) was in the largest firms (100–1000 employees). The distribution of exposure level by workforce size is shown in Fig. 1. The highest level of exposure was recorded in 2006 ($N=237$, $GM=0.039$, 95% $CI=0.034–0.043$) and the largest number of measurements in 2004 ($N=289$, $GM=0.038$, 95% $CI=0.033–0.043$).

Estimating exposed workers

Overall, 41 643 workers were estimated as potentially at-risk of exposure to RCS in the selected industrial sectors between 1996 and 2012. The sector with the greatest percentage of exposed workers was sawing and processing of stones and marble (NACE code: 26.70.1) with 17 380 workers potentially exposed (97% male). For women, the sector with the greatest number of exposed workers was manufacture of ceramic household and ornamental articles (NACE code: 26.21.0) with 2458 workers potentially exposed. Detailed data on the number of exposed workers by industrial sector and gender are shown in Table 3.

Mixed-effects model

One-way analysis of variance showed the variables most related to silica exposure level were: occupation (eta-square=0.574; chi-square=827.29, $P<0.0001$), economical sector (eta-square=0.473; chi-square=722.33, $P<0.0001$), measurement year (eta-square=0.251; chi-square=568.12, $P<0.0001$), and firm size (eta-square=0.141; chi-square=382.94; $P<0.0001$). In the mixed effects model, exposure variables and all interactions (crossed) were analyzed to test independent effects.

Table 2 Descriptive statistics of RCS exposure by occupational group (male only; SIREP, 1996–2012)

Occupational group (ISCO-88 code)	N	NH	AM	GM	GSD	(95% CI)
Miners and quarry workers (7111)	238	230	0.048	0.046	1.443	0.044–0.048
Stone splitters, cutters and carvers (7113)	130	41	0.050	0.015	5.931	0.011–0.021
Carpenters and joiners (7124)	115	107	0.047	0.045	1.469	0.042–0.048
Metal molders and coremakers (7211)	71	17	0.020	0.007	3.968	0.005–0.010
Jewelry and precious-metal workers (7313)	224	42	0.037	0.009	4.395	0.008–0.011
Ore and metal furnace operators (8121)	92	–	0.008	0.007	1.455	0.007–0.008
Glass and ceramics kiln and related machine operators (8131)	124	–	0.022	0.022	1.010	0.022–0.022
Other groups	356	176	–	–	–	–

Note: N: number of 8-hour TWA exposure measurements (mg/m³); NH: number of 8-hour TWA exposure measurements (mg/m³) exceeding the limit proposed by ACGIH; AM: arithmetic mean; GM: geometric mean; GSD: geometric standard deviation; CI: confidence interval.

Only groups with at least 50 exposure measurements are shown.

Figure 1 Distribution of exposure level (GM) and 95% CI by work force size (SIREP, 1996–2012).

Non-significant variables ($P > 0.05$) were excluded stepwise from the model. The fixed-effects of the model explained 84% of the variance in the observed exposure data. In the final model (the lowest value of the Akaike Information Criterion), between- and within-firm variances were $\sigma_B^2 = 0.26$ and $\sigma_W^2 = 1.83$, respectively. The final model is presented in Table 4 and the detailed results are reported as supplementary material

(<http://www.maneyonline.com/doi/suppl/10.1179/2049396714Y.0000000078>).

Discussion

The SIREP system, which tracks data about workers exposed to carcinogens, represents one of the most reliable information sources of occupational exposure to crystalline silica in Italy. In our study, these data

Table 3 Workers potentially exposed to RCS in selected sectors of economic activity (SIREP, 1996–2012)

Economic activity sector (NACE code)	% of firms*	% of workers [†]	No. of exposed [‡] (men)	No. of exposed [‡] (women)	No. of exposed [‡] (all)
Manufacture of ceramic household and ornamental articles (26.21.0)	0.4	1	4261	2458	6719
Sawing and processing of stones and marble (26.70.1)	0.2	1	16 895	485	17 380
Artistic working of marble and other stones; mosaic work (26.70.2)	0.3	1	3690	913	4603
Precious metals production (27.41.0)	7.3	25	50	–	50
Manufacture of jewelry and related articles n.e.c. (36.22.1)	1.1	7	2282	166	2448
Collection, purification and distribution of drinking water (41.00.1)	0.5	6	349	182	531
Other construction work involving special trades (45.25.0)	0.1	4	9912	–	9912
Total	–	–	37 439	4204	41 643

Note: *Percentage of firms in SIREP according to last industry census data;

[†]Percentage of workers in SIREP according to last industry census data.

[‡]Number of estimated exposed workers.

n.e.c.: not elsewhere classified.

Table 4 Final mixed-effects model for RCS exposure (SIREP, 1996–2012)

Effect	DF	Eta-square	Chi-square	F-test	P-value
Geographical location*measurement year	57	0.124	155.45	2.73	<0.0001
Firm size*measurement year	38	0.072	84.68	2.23	<0.0001
Occupation	36	0.046	53.36	1.48	0.03
Geographical location*firm size*measurement year	30	0.036	40.99	1.37	0.09
Measurement year	16	0.026	28.76	1.8	0.03
Geographical location	8	0.014	15.52	1.94	0.05
Activity sector	8	0.014	15.39	1.92	0.05
Activity sector*occupation	6	0.009	10.26	1.71	0.12
Firm size	4	0.003	3.79	0.95	0.44

Note: DF: degrees of freedom; *F*-test: statistical test; *P*-value: statistical significance level. Symbol * denotes a multiplicative interaction (crossed) of variables.

were analyzed to provide a national picture of the working sectors at risk for silica-induced occupational illnesses. A similar approach was previously adopted with concentrations of airborne crystalline silica dust measured during inspections by the US OSHA.¹² Also, multiple national and industry exposure databases from several European countries and Canada were recently used in conjunction with a literature review to empirically model occupational exposure to RCS, resulting in a quantitative job-exposure matrix.¹³

We confirmed that construction and manufacturing of non-metallic minerals, which are sectors that are traditionally considered to expose workers to elevated levels of RCS, had the highest number of reported exposures. Mean air RCS concentration measured in these sectors ($GM=0.045$ and $GM=0.017$, respectively) are in line with concentrations reported in recent years in other European countries and in North America.^{13–17}

According to the 2001 industrial activity census, approximately 863 250 Italian workers are employed in construction.¹¹ Using our data, a reliable estimate of Italian workers exposed to silica was achievable only for a specific subsector of this activity (i.e. other construction work involving special trades, NACE code 45.25.0), corresponding to only 3.3% of the total construction workforce. Moreover, the high variability of exposure levels by trade, type of task and work procedures does not permit an extension of the estimate to the entire sector.^{18–20} However, the subgroup of workers best characterized in our study, including those engaged in stonework masonry and tunnel construction, can reasonably be considered at high risk for adverse health effects as a result of silica exposure based on their higher mean exposure level ($AM=0.057$, 93% of exposure measurements above the ACGIH limit value).^{12,13,18,21} It should also be noted that carpenters and joiners had significant mean RCS exposure levels ($AM=0.047$, 93% of exposure measurements above the ACGIH limit value), comparable with those of miners and quarry workers ($AM=0.048$, 97% of exposure measurements above the ACGIH limit value), likely reflecting an inadequate implementation of preventive

measures to control workplace silica dust air concentrations in the Italian construction industry, similar to other economically developed countries.^{19–21}

We estimate that about 30 000 workers are exposed to crystalline silica in the manufacture of non-metallic minerals in Italy (NACE code 26), referring to three well-defined subsectors (NACE codes: 26.21.0, 26.70.1, and 26.70.2, representing 21% of the whole sector). In the US working population, a mean RCS concentration of 0.025 mg/m^3 was measured in tile, marble and mosaic work, compared to 0.075 mg/m^3 in cut stone and stone products in 1988–2003.¹² Similarly, in our study, exposure levels in the manufacture of non-metallic minerals were found to vary between and within occupations, leading to an overall mean concentration lower than in construction, as well as a smaller percentage of TLV overwhelming values. This may be due to the significant decrease of airborne RCS concentrations reported in the ceramic industry over time,^{14,22} and to the high variation in whether workers use dry or automated/remotely controlled working methods.¹⁵ A number of female workers were also estimated to be exposed to RCS in this sector, particularly in the ceramic ($N=2458$) and the artistic stone working industry ($N=913$). These data should be considered to build up occupational disease surveillance and reporting systems and to adopt proper compensation policies.^{23,24} Moreover, specific preventive interventions are recommended in this sector to protect women's health during pregnancy and lactation.

In the manufacturing of basic metals, we found lower mean air RCS concentrations compared to other studies, but found similar values to a more recent study in a Swedish iron foundry.^{12,25} Our data, which were based on non-mandatory reporting, and the high variability of reporting coverage over time may explain these findings. We found that the year of measurement interacted with other variables, such as firm size and geographic area, to predict reported RCS concentrations.

The results of this study also identified additional sectors with RCS exposure, such as jewelry manufacturing with an estimated 2 500 exposed workers.

In comparison with other metal-related jobs, jewelry and precious metal workers were exposed to a higher mean RCS concentration, with a notable number of measurements above the ACGIH TLV. These workers, although they represent a small proportion of Italian workers, should be targeted for prevention measures, including dust abatement programs and risk awareness education initiatives.²⁶

Overall, 50% of exposed workers had an exposure value exceeding the limit (TLV) proposed by ACGIH (and 44% had exposure values exceeding SCOEL recommendations). This indicates that there is a need for addition and more intense dust control and information interventions. These control and intervention measures should target sectors, such as construction, at greater risk of exceeding occupational exposure threshold limits. The recommendations arising from our findings will assume a greater weight both at company and at sector level if a law with a stricter exposure limit value is adopted in Europe to protect workers from health risks associated with silica dust exposure.

The analysis of exposure determinants shows that in addition to occupation, firm size and location also significantly influenced RCS exposure level. Mean air concentrations of RCS were higher in larger-sized firms. This may be partially explained by larger firms possibly being more proactive and more likely to adopt preventive health safety practices compared to small firms, which may lack work safety experts.²⁷ In the multivariate analysis model, firm size and geographic location were dependent from measurement year, possibly reflecting the poor homogeneity of reporting in Italy during the study period. Nevertheless, the dependence of exposure levels on a large set of variables calls for caution in the interpretation of the results shown in Tables 1 and 2, and highlights the need for further analyses.

The primary limitation of this study is the incomplete territorial coverage of SIREP database. This makes it impossible to compare crystalline silica exposure among different regions, despite the influence of geographic area suggested in the results. Another study limitation is the source of the data. Data collection and reporting for the SIREP database is the responsibility of the employer, and we observed that the number of exposure measurements differed by industrial sector and firm size. Uncertainty may have also been introduced as a result of differences in air sampling, analytical procedures, and sample collection methods (personal or stationary). We controlled for differences between firms by introducing firm as a random effect in the statistical model. Bias may also have been introduced into the exposure estimate by substituting censored data (measurements below the LOD) with LOD/2. Conversely, a strength of the study is the use of mixed effects statistical model that was able to account for both fixed

and random effects, and to handle unbalanced data. In order to increase the precision of estimates, only sectors and occupations having more than 50 measurements recorded were included in the descriptive analysis. Information campaigns aimed to increase RCS exposure reporting, especially targeting small enterprises, will allow confirmation of our findings in a wider sample of firms. A follow-up step is to conduct national and/or industry-specific surveys to investigate firm-related factors affecting RCS air concentrations. These surveys should include the assessment of environmental conditions, control measures, and workers' use of personal protective equipment for which no information is available in SIREP database.

The highly variable level of reporting resulted in a limited estimate of the number of exposed workers in certain economic subsectors. The number of exposed workers in each sector was calculated assuming the same ratio between exposed and non-exposed workers in firms reporting and non-reporting exposures data, which may have biased the estimates. A larger number of firms and workers were expected to be included in the SIREP database according to a former evaluation of exposed workers to RCS.⁴ This smaller observed number may be due to lack of uniform and standardized criteria in defining a worker as occupationally exposed to carcinogens, particularly if the exposure level is low, and due to the discrepancy in the classification of RCS as a hazardous substance among international authorities and in labeling of RCS containing mixtures. Moreover, our estimate for females likely does not apply to certain economic sectors since the percentage of exposed workers was computed using a small sample. A possible misclassification of some variables (e.g. industrial sector or job/occupation) may have also occurred, although its effect is partially reduced by the use of standard international classifications. Despite these limitations, the results provide a baseline to discerning patterns of occupational exposure to crystalline silica in Italy and can be used to inform future prevention and research.

These activities should be focused on the reduction of air RCS to the minimum level by promoting the use of proper dust control measures and a greater awareness of the health risks associated with occupational exposure to crystalline silica.

In conclusion, our analysis identified a number of sectors characterized by significant occupational exposure to crystalline silica. We described activity subsectors and occupations at high risk for silica-induced diseases and provided select nation-level estimates of exposed workers. Some of these subgroups of workers, mainly in the construction sector, should be the specific target of information campaigns on chemical safety and cancer prevention at workplace. Policy makers and health local authorities should use our data for program

regulatory and inspection interventions in order to promote a reduction of mean air RCS concentrations.

Disclaimer Statements

Contributors Alberto Scarselli designed the study's analytic strategy and made its implementation; Marisa Corfiati helped to conduct the literature review, to interpret the results and drafting the paper; Davide Di Marzio helped conduct the data acquisition and analysis; Sergio Iavicoli contributed to the study's conception and supervised its implementation.

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