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Original Article

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Determinants of Respirable Quartz Exposure Concentrations Across Occupations in Denmark, 2018

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Abstract

Background: High concentrations of respirable quartz have been reported from workers in construction, foundries, and quarries. Current exposure concentrations in prevalent but presumably lower exposed occupations have been less examined. We aimed to quantify current exposure concentrations of respirable dust and quartz across prevalent occupations and to identify determinants of respirable quartz exposure across these occupations.

Methods: One hundred and eighty-nine full-shift personal samples of respirable dust of workers within 11 occupations in Denmark were sampled during 2018. Respirable dust was determined gravimetrically and analysed for quartz content with infrared spectrometry. Determinants for respirable quartz exposure, i.e. use of power tools, outdoor or indoor location, and percentage of quartz in respirable dust, were analysed in linear mixed effect models.

Results: The overall geometric means (geometric standard deviations) for respirable dust and quartz were 216 µg m^{-3} (4.42) and 16 µg m^{-3} (4.07), respectively. The highest quartz concentrations were observed among stone cutters and carvers [93 µg m^{-3} (3.47)], and metal melters and casters [61 µg m^{-3} (1.71)]. Use of power tools increased exposure concentrations of quartz by a factor of 3.5. Occupations explained 27%, companies within occupations 28%, and differences between workers within companies within occupations 14% of the variability in quartz concentrations. Thirty percent was due to day-to-day variability in exposure concentrations. In total, 19% of the variation in quartz

concentration could be explained by type of tool, indoor/outdoor location, and percentage of quartz in respirable dust.
Conclusion: Current exposure concentrations are generally low, but some occupations in this study had average exposure concentrations to respirable quartz above the ACGIH threshold limit value of 25 µg m^{-3}. Preventive measures to lower excess risk of quartz-related diseases among these workers are still needed. In terms of preventive strategies, use of power tools and quartz content of used materials were identified as main determinants of exposure. Lowering of exposures will be most efficient when focussed on these major determinants, e.g. tool dust control with water, dust extraction, and use of low quartz content materials.

Keywords: determinants of exposure; exposure variability; mixed effect model; occupational exposure; quartz exposure; respirable dust; silica exposure; work place measurements

What's Important About This Paper?

Exposure to respirable quartz is a well-documented workplace hazard in some highly exposed occupations. However, exposure concentrations in a number of prevalent, but less-exposed jobs are not well described. This study measures quartz exposure levels across a number of occupations and examine determinants for exposure concentrations together with variance components within and between workers, occupations, and companies. The study adds important knowledge to be used in preventive strategies.

Background

Crystalline silica is present in most rocks and is a major constituent of sand and soil. Alpha-quartz is the most abundant of several forms of crystalline silica (IOM, 2011; IARC, 2012). The general population is exposed to low levels of airborne crystalline silica through outdoor and indoor sources, for example resuspension of settled dust indoors, and silica-containing commercial products (i.e. cosmetics, cleansers, pet litter, putty, and paint) (IARC, 2012; Roney *et al.*, 2019). Workers in agriculture, construction, mining, quarrying, and manufacturing of metal products may be exposed to high concentrations of respirable silica (Peters *et al.*, 2011; IARC, 2012). Respirable crystalline silica exposure is a well-documented risk factor for silicosis (t Mannetje *et al.*, 2002) and lung cancer (IARC, 2012; Ge *et al.*, 2020) and is associated with the occurrence of rheumatoid arthritis, systemic sclerosis, and other autoimmune rheumatic diseases (Miller *et al.*, 2012; Boudigaard *et al.*, 2021).

In general, exposure concentrations of respirable crystalline silica have declined over the past 50 years (Yassin *et al.*, 2005; Creely *et al.*, 2007; Peters *et al.*, 2011; Zilaout *et al.*, 2020), but high concentrations are still reported in foundries (Andersson *et al.*, 2009; Radnoff *et al.*, 2014), the stone and brick sector (Healy *et al.*, 2014; Radnoff *et al.*, 2014; Baldwin *et al.*, 2019), and in construction (Radnoff *et al.*, 2014; Bello *et al.*, 2019). It was estimated that 5.3 million workers in Europe were potentially occupationally exposed to respirable crystalline silica in 2006, of which 75% were employed in construction (IOM, 2011). However, not all construction workers are exposed to high concentrations (Hammond *et al.*, 2016). To implement an efficient preventive strategy, knowledge on exposure concentrations in prevalent, but less-exposed jobs are warranted in addition to the known high exposed jobs.

The aim of the present study is to quantify current exposure concentrations of respirable quartz and to identify determinants of exposure across occupations.

Materials and methods

Companies and participants

Based on the prevalence of occupations in Denmark with expected quartz exposure (BGIA, 2008; Peters *et al.*, 2011; IARC, 2012), we identified companies employing construction-, metal-, and concrete workers and farmers. Occupations were classified based on the four-digit level of the Danish version of the International Standard Classification of Occupations, ISCO-88 (ILO, 2004). Industry was classified at two-digit level of the European classification of industries, NACE vers.2 (The European Parliament and Council of the European Union, 2006) (Table 1, Supplementary Table S1). We prioritized inclusion of companies of different sizes, and when feasible companies with employees from more than one relevant occupation located in the eastern part of Jutland. A total

Table 1. Characteristics, respirable dust and respirable quartz (µg m^{-3}) among 140 persons, Denmark, 2018

	Persons	Samples	Respirable dust		Quartz		Respirable dust µg m^{-3}			Quartz µg m^{-3}			% of quartz in respirable dust	Quartz µg m^{-3} (>LOD) min–max	Exceedance (%)[c]
Characteristics	K	N	<LOD[a]	%	<LOD[b]	%	AM	GM	GSD	AM	GM	GSD			
Occupational group (ISCO88)															
7113. Stonecutters and carvers	10	15	0	0	0	0	1224	534	3.44	199	93	3.47	18	20–1083	48
7122. Bricklayers and stonemason	17	24	3	13	9	38	260	86	5.32	57	21	4.36	30	10–194	15
7123. Concrete placers, finishers and related	16	23	1	4	12	52	152	114	2.30	14	8	1.92	14	9–56	<1
7129. Building frame and related trades workers	21	21	0	0	3	14	1554	741	2.83	57	34	2.95	7	9–179	16
7220. Blacksmiths, tool-makers and related	9	11	0	0	7	64	1038	718	2.50	21	9	4.78	9	25–121	6
8112. Mineral, ore or stone processing-plant operators	8	11	0	0	3	27	304	185	3.00	39	22	4.06	17	11–196	14
8122. Metal melters, casters and rolling-mill operators	10	18	0	0	0	0	1032	719	1.97	69	61	1.71	11	24–165	18
8131. Glass, ceramics kiln and related machine operators	17	22	0	0	10	45	394	297	2.27	21	12	2.26	6	10–58	1
8212. Cement/other mineral products machine operators	7	11	0	0	8	73	196	176	1.55	13	5	1.72	7	9–22	<1
8332. Earth-moving- and related plant operators	10	14	5	36	10	71	41	25	2.57	10	4	2.95	19	10–14	<1
9310. Mining and construction labourers	15	19	1	5	9	47	154	94	2.88	18	10	2.49	17	10–71	1
Industry (NACE, rev.2)															
8. Other mining and quarrying	10	14	0	0	3	21	337	209	2.90	41	22	3.41	16	11–196	11
23. Manufacture of other non-metallic mineral products	34	48	0	0	18	38	597	311	2.69	72	20	4.81	10	9–1083	15
24. Manufacture of basic metals	10	18	0	0	0	0	1032	746	1.97	69	60	1.71	11	24–165	17
25. Manufacture of fabricated metal products, except machinery and equipment	7	8	0	0	7	88	1200	888	2.45	13	3	3.75	8	25–25	<1
41. Construction of buildings	7	14	1	7	11	79	136	88	2.73	16	5	3.85	25	11–55	1
42. Civil engineering	16	21	0	0	12	57	169	111	2.48	19	8	3.11	16	10–71	1
43. Specialized construction activities	56	66	9	14	20	30	688	153	6.68	42	18	3.58	16	9–194	9
Tool															
None	15	19	0	0	11	58	424	254	2.47	19	8	2.40	8	9–58	<1
Use of hand tools	44	72	4	6	32	44	398	197	3.98	33	15	3.82	17	10–165	8
Use of power tools	40	46	0	0	8	17	1224	462	4.15	90	30	4.36	13	9–1083	21
Operating construction machines	41	52	6	12	20	38	287	110	4.37	26	13	3.27	16	9–196	4
Location															
Indoor	68	93	0	0	27	29	916	478	2.78	62	23	3.82	10	9–776	14
Outdoor	72	96	10	10	44	46	309	100	4.33	30	12	4.11	19	9–1083	6
Total	140	189	10	5	71	38	604	216	4.42	46	16	4.07	15	9–1083	10

[a]LOD for respirable dust = 24 µg m^{-3}.
[b]LOD for respirable quartz = 9 µg m^{-3}.
[c]Exceedance of OEL 100 µg m^{-3}.

of 38 companies were approached; 15 large companies with more than 100 employees and 23 small companies with less than 100 employees. In total 24 companies (63%) agreed to participate of which 5 employed workers from more than one relevant occupation. Sixty percent of the large companies and 65% of the small companies accepted the invitation. Farmers were contacted through a farmers' trade associations; however, no farmers were recruited.

Managers at the worksites were instructed to select up to eight employees with work tasks representative for the targeted occupations.

Sampling and analytical method

On the measurement day, participants filled in a questionnaire about primary task, tools, or construction machines used, whether their work location was indoor or outdoor, and use of a respirator. We conducted full-shift measurements; however, pumps were turned off during breaks lasting more than 15 min. Measurements with sampling time below 4 h were excluded. All companies were asked to participate in a second measuring round. If they agreed, repeated measurements were carried out on study participants who remained at the worksite. All measurements were carried out by the same technician between April and December 2018.

Respirable dust was collected on 25-mm PVC filters using a conductive plastic sampler with a respirable dust cyclone (SKC LTD conductive plastic cyclone) connected to SKC AirChek XR5000 portable pump (SKC Inc., Eighty-Four, PA) calibrated at a flow rate of 2.2 l/min. The cassette was attached to the upper part of the participant's chest within the breathing zone.

Respirable dust was determined gravimetrically. Filters were conditioned for a minimum of 24 h (22°C, 45% relative humidity) before weighing using a Mettler UMT2 analytical scale (Mettler-Toledo Ltd, Greifensee, Switzerland) with 0.1-mg precision. One field blank was included per visit (n = 45). The lower limit of detection (LOD) for respirable dust was calculated as three times the Standard deviation (SD) of the weight changes of the field blanks, corresponding to a concentration of 24 µg m^{-3}, when assuming 8-h measurements.

Quartz was determined by Fourier transform infrared spectrometry, in accordance with MDHS 101/2 (HSE, 2014). The analytical level of quantification for quartz was 10 µg, assuming 8-h measurements correspond to a concentration of 9 µg m^{-3}.

Statistical analysis

Respirable dust and respirable quartz concentrations were log normally distributed, assuming values below LOD followed the same distribution. Hence, statistical analyses were performed using log-transformed values. We used mixed effects Tobit models (metobit, Stata) for interval censored data. All left censored values (values below LOD) were assumed to be in an interval between (-∞) and the LOD (Hughes, 1999; StataCorp., 2019).

In the applied mixed effect models, worker, company, and occupation were included as random effects, and tool, location, and percentage of quartz in respirable dust as fixed effects. β-coefficients are displayed as Exp β with 95% confidence intervals (CI). Geometric standard deviation factor (GSD) was calculated asexp $\left(\sqrt{\sigma_{wY}^2 + \sigma_{bY}^2}\right)$, where σ_{wY}^2= within-worker variance and σ_{bY}^2 = between-worker variance. The occupational exposure limit (OEL) in Denmark and several European countries is 100 µg m^{-3} (The European Parliament and Council of the European Union, 2017), and we calculated the exceedance fraction above as $P\left[Z > \frac{\ln(OEL)-\ln(GM)}{\ln(GSD)}\right]$.

If an occupational group was represented by less than 10 persons on ISCO-88 major group 4 level, it was merged with similar occupations on the corresponding ISCO-88 major group 3 level. Tool was categorized into no tool, hand tools, power tools, and operating construction machines. Location was dichotomized into primarily working inside or outside (Table 1, Supplementary Table S1). The percentage of quartz in respirable dust was imputed for quartz measurements below LOD (38%). For the majority of missing values, we used the median of the percentage of quartz from other workers doing the same job at the same company. For the remaining seven missing values, where none of the co-workers had detectable values of quartz, we used the median percentage from all workers in the same job and company using the estimated LOD value of quartz.

All analyses were carried out using Stata, version 16 and 17.

Results

We performed 194 measurements on 143 participants. One measurement was lost during transportation and four with a sampling time of less than 4 h did not fulfil our inclusion criteria and were excluded, leaving 189 measurements from 140 participants for further analyses. The median sampling time was 428 min, with an interquartile range of 367–456 min. Repeated measurements were available for 35% of the participants, with a median duration between the two measurements of 91 days, interquartile range 84–125 days.

All together 15% of workers (21 participants) reported use of respirators at some point during the day, with missing information from 5% of the measurements. For nine participants using respirators, quartz concentrations were below the LOD, and the range in concentrations among workers using respirators was from 11 to 1083 µg m^{-3}. The majority (68%) of the respirator users reported using power tools, 45% were employed in a large company (<100 employees), and 55% in a smaller company.

Five percent of the respirable dust measurements and 38% of the quartz measurements were below LOD (Table 1). Thirteen percent of all measurements were above the OEL. Measured quartz concentrations ranged from values <LOD to 1083 µg m^{-3}. Stone cutters and carvers were the only occupation having measurements with concentrations above 200 µg m^{-3} and had a probability of exceedance of 48%. Construction workers (bricklayers, stonemasons, and other building frame workers), mineral or stone processing-plant operators, and metal melters and casters had lower quartz concentrations and probability of exceedance between 14 and 18% (Table 1).

The geometric mean, GM (geometric standard deviation, GSD) for respirable dust exposure concentration was 216 µg m^{-3} (4.42). Highest exposure concentrations were found among demolition workers and scaffolding fitters (included in the building frame workers category), with a GM of 741 µg m^{-3} (2.83), metal melters and casters with a GM of 719 µg m^{-3} (1.97), and blacksmiths with a GM of 718 µg m^{-3} (2.50) (Table 1).

The GM (GSD) of overall quartz exposure concentration was 16 µg m^{-3} (4.07). Highest concentrations were observed among stonecutters and carvers, GM of 93 µg m^{-3} (3.47), and metal melters and casters, GM of 61 µg m^{-3} (1.71) (Table 1). Percentage of quartz in respirable dust varied from 6 to 30% across occupations. Highest percentage were seen among bricklayers and stonemasons (Table 1).

Use of hand or power tools compared with no tools increased quartz exposure concentrations, e.g. use of power tools resulted in a 3.5 times higher exposure [exp(β) = 3.46 (1.66–7.21)] (Table 2). The quartz content was also an important determinant, with 3 percentage increase in quartz exposure concentration for each percent increase in quartz content in respirable dust.

Of the total variance, occupations explained 27%, companies within occupations 29%, and workers within a company within an occupation 14% of the variability in quartz concentrations. Thirty percent was due to day-to-day variability in quartz concentrations. Including tool and location as fixed effects into the model explained 13% of the total variability, primarily decreasing the variability between workers within companies and occupations (35% explained). When percentage of quartz in respirable dust was added, the fixed effects explained 19% of the total variability, 38% of the variability between occupations, 14% between companies within occupation, and 29% between workers within companies and occupations (Table 3).

Discussion

Based on 189 measurements, respirable dust and quartz exposure concentrations was generally low across the 11 sampled occupations, but a few occupations had high average concentration. Furthermore, a number of the measurements showed quartz concentrations well above the OEL. Use of power tools and quartz percentage in respirable dust were the most important determinants of quartz exposure concentrations and explained much of the variability in quartz concentrations between companies and between workers within companies and occupations.

We have included several prevalent, moderately to highly exposed occupations. However, the size of the sample limits the number of occupations and persons within each occupation, potentially affecting the accuracy of the estimated exposure concentrations. The exposure concentrations found in our study are generally in line with concentrations observed in similar occupations, if reported yearly decreasing exposure trends are taken into account (Yassin *et al.*, 2005; Creely *et al.*, 2007; Peters *et al.*, 2011; Zilaout *et al.*, 2020). In our study, metal melters and casters are among the highest quartz exposed occupations, and our results indicate slightly lower exposure concentrations compared with results from iron foundries in Sweden from 2005, where the authors reported overall exposure concentrations (GM) of respirable quartz of 280 µg m^{-3} (Andersson *et al.*, 2009). Compared with our results, slightly lower exposure concentrations from the non-ferrous foundry industry in Canada were reported, with GM of 25 µg m^{-3} from 2009 to 2013 (Radnoff *et al.*, 2014).

Compared with earlier studies of construction workers (Rappaport *et al.*, 2003; Tjoe Nij *et al.*, 2004; Peters *et al.*, 2011; Radnoff *et al.*, 2014; van Deurssen *et al.*, 2014; Baldwin *et al.*, 2019; Bello *et al.*, 2019), we find similar or lower quartz concentrations. Measurements from 2009 to 2013 in Canadian construction workers showed a GM of respirable quartz of 105 µg m^{-3} among bricklayer and concrete finisher (Radnoff *et al.*, 2014). Our study shows comparable exposure concentrations with those reported in SYNJEM for bricklayers (GM average of 30 µg m^{-3} across Europe and Canada in 1998, ranging from 20 to 70 µg m^{-3}) and from a study of bricklayers in the Netherlands in 2014 (20 µg m^{-3}) (van Deurssen *et al.*, 2014).

Table 2. Determinants of respirable quartz concentration (μg m^{-3}), 189 personal measurements among 140 workers, Denmark, 2018

	Exp (β)	95 % CI	*P*-value
Model including fixed effects: Occupation, company, and worker as random effects, tool and location as fixed effects			
Intercept	6.66	2.80–15.81	<0.001
Tool			
None (REF)	1		
Use of hand tools	2.20	1.04–4.65	0.038
Use of power tools	3.51	1.66–7.41	0.001
Operating construction machines	1.82	0.87–3.82	0.114
Location			
Indoor	1.21	0.69–2.12	0.511
Outdoor (REF)	1		
Model including fixed effects: Occupation, company and worker as random effects, and tool, location and content of quartz in dust as fixed effects			
Intercept	4.12	1.65–10.25	0.002
Tool			
None (REF)	1		
Use of hand tools	2.18	1.05–4.53	0.036
Use of power tools	3.46	1.66–7.21	0.001
Operating construction machines	1.76	0.85–3.64	0.127
Location			
Indoor	1.40	0.79–2.46	0.250
Outdoor (REF)	1		
Content of quartz in respirable dust			
Per 1% increase in quartz content	1.03	1.01–1.05	0.010

Table 3. Variance components for respirable quartz level from models excluding and including fixed effects

	Model excluding fixed effects	Model including tool and location as fixed effects	% explained	Model including tool, location and the content of quartz in dust as fixed effects	% explained
Between-occupation variance	0.53	0.45	15	0.33	38
Between-company variance	0.56	0.46	17	0.48	14
Between-worker variance	0.28	0.18	35	0.20	29
Within-worker variance	0.60	0.63	−5	0.58	3
Total variance	1.97	1.72	13	1.59	19

If companies with low dust exposure concentrations were more inclined to participate in the study, the observed exposure concentrations would underestimate the true exposure levels. In Denmark, companies decide how to monitor the working environment, but they have to comply with the occupational exposure limit (OEL) for silica and dust. Quantitative monitoring (measurements) is not routinely performed by the working environment authority. Hence, it is possible that larger companies with a working environment organization and regularly dust exposure monitoring would be more prone to participate in this study. We tried to take this potential selection bias into account by recruiting both small and large companies, and they have similar participation rates, 65 and 60%, respectively. The selection of the sampled workers by managers might have biased the results, but given that we selected the jobs and the (unpredictable) large day-to-day variability in exposure concentrations we consider this bias to be minimal.

Self-reported information on indoor vs. outdoor location and tool used could be misclassified. However, since the workers are unaware of exposure concentration to respirable quartz, this should be non-differential and would primarily attenuate the shown effect of location and tool.

The use of SKC LTD plastic cyclone has potentially resulted in oversampling of respirable quartz (Verpaele and Jouret, 2013). In the mixed effect model, the potential oversampling should have no effect on modelling determinants of exposure and estimation of the variance components.

Approximately one third of all quartz measurements were below LOD. This has to be taken into account in accepting the assumption of log normality. Furthermore, how these very small values are treated will highly effect the GM (Hewett and Ganser, 2007). Due to high numbers of values below LOD in our study, we refrained from imputation of the left censored values. Instead, we used a Tobit model that takes the distribution probability of the missing values into account. We assume that this should not have a major effect on comparability of mean exposure concentrations with studies using imputation techniques. We did however impute the percentage of quartz, when quartz and/or respirable dust was below the LOD. When we restricted the analysis to measurements above LOD as expected more variability in exposure concentrations was explained (55% of total variability, results not shown).

Use of power tools and percentage of quartz are the main determinants for increased quartz exposure concentrations. The effect of power tools corresponds well with findings from other studies among construction workers (Healy *et al.*, 2014; Baldwin *et al.*, 2019). Percentage of quartz in dust reflects the material used and explains some of the difference in exposure concentrations between occupations. Hence, in terms of preventive strategies, control measures for power tools (e.g. tool dust control with water and dust extraction) and substitution of materials with high quartz content will lower quartz exposure concentrations, as well as reducing differences between occupations and to a lesser extend companies.

Conclusion

Even though exposure concentrations in 2018 across many occupations in Denmark generally are low, some prevalent occupations had average exposure concentrations to respirable quartz above the ACGIH threshold limit value of 25 µg m^{-3}. Preventive measures to lower excess risk of diseases among these workers are still needed. In terms of preventive strategies, use of power tools and quartz content of materials worked with were identified as main determinants of exposure. Lowering of exposures will be most efficient when focused on these major determinants.

Supplementary data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Conflict of interest

HKr receives funding from the Industrial Minerals Association Europe for maintaining and analysing exposure data from their Dust Monitoring Programme (https://www.ima-europe.eu/commitments/dust-monitoring-programme). The authors declare no other conflict of interest relating to the material presented in this paper. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

Data availability

The data underlying this paper cannot be shared publicly due to the privacy of the individuals and companies who participated in the study, but data can be shared in an anonymized form on reasonable request to the corresponding author.

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