Annals of Work Exposures and Health, 2023, **67**, 392–401
https://doi.org/10.1093/annweh/wxac093
Advance access publication 3 January 2023
Original Article

BOHS British Occupational Hygiene Society
The Chartered Society for Worker Health Protection
OXFORD

Temporal Trends in Variability of Respirable Dust and Respirable Quartz Concentrations in the European Industrial Minerals Sector

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Abstract

While between- and within-worker variability have been studied quite extensively, hardly any research is available that examines long-term trends in the variability of occupational exposure. In this first study on trends in occupational exposure variability temporal changes in the variability of respirable dust and respirable quartz concentrations within the European industrial minerals sector were demonstrated. Since 2000 the European Industrial Minerals Association's Dust Monitoring Program (IMA-DMP) has systematically collected respirable dust and respirable quartz measurements. The resulting IMA-DMP occupational exposure database contains at present approximately 40 000 personal full-shift measurements, collected at 177 sites owned by 39 companies, located in 23 European countries. Repeated measurements of workers performing their duties within a specific site-job-campaign combination allowed estimation of within- and between-worker variability in exposure concentrations. Overall day-to-day variability predominated the between-worker variability for both respirable dust concentrations and quartz concentrations. The within-worker variability in concentrations by job was two to three times higher for respirable quartz than for respirable dust. The median between-worker variability in respirable dust concentrations was low and further reduced over time. For quartz concentrations the same phenomenon albeit somewhat less strong was observed. In contrast, for the within-worker variability in concentrations downward and upward temporal trends were apparent for both respirable dust and respirable quartz. The study shows that the (relative) size of temporal variability is large and unpredictable and therefore regular measurement campaigns are needed to ascertain compliance to occupational exposure limit values.

Keywords: between-worker; exposure variability; industrial minerals; long-term trends; respirable dust; respirable quartz; variance components; within-worker

What's Important About This Paper?

While there has been a lot of research that documents a general decrease in workplaces over time, there has been less exploration of patterns of exposure variability. Using respirable dust and quartz monitoring data collected by the European Industrial Minerals Associations Dust Monitoring Programme (IMA-DMP), this study demonstrated that within- and between-worker variability did not exhibit monotonic trends over time. This suggests that exposure variability should be explored, along with magnitude, over time as it may indicate changes in exposure patterns, such as control performance and job assignments.

Introduction

Since it has been generally recognized that occupational exposure concentrations are highly variable, estimation of between- and within-worker variability in exposure concentrations has been considered to be an essential key factor when designing efficient exposure assessment strategies (Kromhout and Vermeulen, 2001), for effective control measures (Vermeulen *et al.*, 2000),

Received: June 27, 2022. Accepted: December 5, 2022.

a valuable exposure surveillance tool (Loomis and Kromhout, 2004), for testing compliance with occupational exposure limits (Rappaport *et al.*, 1995) and to prevent or adjust attenuation of exposure–response relationships in epidemiological analyses (van Tongeren *et al.*, 1997).

In 1993 Kromhout *et al.* (1993) published a comprehensive evaluation of between- and within-worker variability in full-shift exposure concentrations within a large variety of occupational settings, showing that exposure concentrations generally differed more from day-to-day (within-worker variability) than from worker-to-worker (between-worker variability) within group of workers performing the same job at the same location. In addition, the results showed that environmental and process characteristics clearly influenced day-to-day variability in exposure concentrations. A meta-analytical review by Symanski *et al.* (2006) confirmed within-worker variability for a group of workers to be generally larger than the between-worker variability. Analyses of a database of occupational dermal exposure measurements showed also greater within-worker variability than between-worker variability (Kromhout and Vermeulen, 2001).

Long-term trends in (average) exposure concentrations have been studied extensively (Creely *et al.*, 2007; Peters *et al.*, 2011, 2017; Schonfeld *et al.*, 2017; Zilaout *et al.*, 2020) and have shown predominantly downward trends. So far long-term trends in within- and between-worker variability have hardly been studied mainly because repeated workplace measurements collected over long time periods in the same workplaces are hardly available. We are aware of only one repeated cross-sectional study, conducted within the rubber manufacturing industry in The Netherlands, which addressed temporal changes in exposure concentrations, but also studied changes in within- and between-worker exposure variability over a 9-year period (Vermeulen *et al.*, 2000). The authors reported a considerable reduction of inhalation and dermal concentrations of rubber dust and fumes, which was accompanied with a significant reduction of both between- and within-worker variability in exposure concentrations.

In 2000, the European Industrial Minerals Association (IMA-Europe) initiated a large prospective dust monitoring program (IMA-DMP) within its member companies to systematically monitor occupational exposure to respirable dust and in particular to respirable crystalline silica (RCS) (Zilaout *et al.*, 2017). One of the goals of the IMA-DMP was to provide companies with insight in exposure levels of their workers and to check compliance with national occupational exposure limits. Furthermore, IMA-DMP aimed to monitor long-term exposure trends, to identify hot spots with high exposure levels and to implement targeted control measures to reduce workers' exposure. The resulting IMA-DMP occupational exposure database contains at present approximately 40 000 personal full-shift measurements of respirable dust and respirable quartz, collected systematically at 177 sites owned by 39 companies, located in 23 European countries. Another important feature of the IMA-DMP is that a considerable amount of repeated measurements of workers within a specific site-job-campaign combination exist, allowing estimation of between- and within-worker variability for workers performing similar jobs at a specific location within a measurement campaign.

In a previous paper we estimated long-term trends in exposure concentrations to respirable dust and respirable quartz for workers within IMA-DMP, over a 15-year period (2002–2016) (Zilaout *et al.*, 2020). In the current paper we analyse the long-term trends in exposure variability over a slightly longer period (2002–2018). As far as we know, this is the first prospective exposure monitoring study allowing estimation of long-term trends in between- and within-worker variability, within an entire European industrial sector over almost two decades. Our objectives were threefold:

i. To estimate between- and within-worker variability in full-shift respirable dust and respirable quartz concentrations overall and by job.
ii. To estimate temporal trends in between- and within-worker variability in full-shift respirable dust and respirable quartz concentrations.
iii. To study the interrelationship between long-term trends in average exposure concentrations and exposure variability.

Methods

Data collection

As of 1 August 2019, the IMA-DMP database (Zilaout *et al.*, 2017) consisted of 38 670 respirable dust and 33 860 respirable quartz personal measurements collected in 37 sampling campaigns between winter 2000/2001 and winter 2018/2019. In our previous paper (Zilaout *et al.*, 2017) we have described in detail the organizational structure within the IMA-DMP, and the procedures outlined in the IMA-DMP standardized protocol, including (i) sampling strategy, (ii) sampling methods, (iii) quality control, (iv) confidentiality requirements and (v) data management. This protocol is adhered to by participating companies of the IMA-DMP to allow for interpretation and comparison of measurement results across the entire industrial sector.

Data selection

First, measurements with extreme concentrations (>100 mg/m^3 for respirable dust and >10 mg/m^3 for respirable quartz) were excluded. Secondly, measurements with a sampling duration shorter than 4 h and longer than 10 h as well as measurements without a unique worker code were also excluded. Thirdly, the first three sampling campaigns (campaigns 1-3) and the most recent campaign (campaign 37) were not considered because of limited amounts of measurement data available.

Subsequently, additional criteria were applied for *each* specific site-job-campaign combination: (i) at least five measurements had to be present, (ii) from at least two workers and (iii) at least one worker should have a repeated measurement. Applying these criteria resulted in a dataset of 17 161 respirable dust and 14 984 respirable quartz shift-long measurements collected between summer 2002 and summer 2018 during 33 campaigns (campaign 4–campaign 36).

As published earlier, appropriate correction factors were applied to account for differences in sampling and analytical efficiency between used respirable dust samplers and collection media (filters versus foam) (Zilaout *et al*., 2020).

Statistical analysis

All statistical analyses were carried out in SAS software version 9.4 (SAS Institute, Cary, North Carolina, USA). Exposure concentrations were log-normally transformed before statistical analyses. A multiple imputation procedure was used to account for exposure concentrations below the limit of detection in order to prevent overestimation of measures of central tendency and underestimation of exposure variability (Jin *et al*., 2011). We repeated the imputation procedure 20 times to allow for uncertainties in imputed data.

Linear mixed models (PROC MIXED) were used to estimate the between- and within-worker variability for each site-job-campaign combination. We repeated the statistical analyses for each imputed dataset and summarized the results by using PROC MIANALYZE to account for imputation variability.

The linear mixed model for each site-job-campaign combination was as follows:

$$Y_{ij} = \ln\ (X_{ij}) = \mu_y + \beta_i + \varepsilon_{ij},\ \text{for}\ (i = 1,\ 2,\ \ldots, k)\ \text{and}\ (j = 1,\ 2,\ \ldots, n_i),$$

Where

X_{ij} = exposure concentration of the i-th worker measured on the j-th day,

μ_y = mean of Y_{ij},

β_i = random deviation of the i-th worker's true exposure $\mu_{y,i}$ from μ_y, and

ε_{ij} = random deviation of the i-th worker's exposure on the j-th day from his or her true exposure, $\mu_{y,i.}$

It is assumed under the model that both β_i and ε_{ij} are normally distributed. From the variance components the standard deviations were estimated for the within-worker ${}_{w}S_{y}$ and between-worker distributions ${}_{b}S_{y}$. These standard deviations were used to estimate the corresponding geometric standard deviations ${}_{W}S_{G} = \exp({}_{w}S_{y})$ and ${}_{B}S_{G} = \exp({}_{b}S_{y})$. Fold-ranges, the ratio of the 97.5th and 2.5th percentiles of the within-worker (${}_{w}R_{0.95}$) and the between-worker (${}_{B}R_{0.95}$) exposure distributions were consequently estimated using the following formulas:

${}_{w}R_{95} = \exp\ (3.92\ {}_{w}S_{y})$ and ${}_{B}R_{0.95} = \exp\ (3.92\ {}_{b}S_{y})$ (Rappaport *et al*., 1991). Fold-ranges were estimated for each combination of site, job, and campaign and summarized by type of exposure and job. Rappaport *et al*. (1991) proposed ${}_{B}R_{0.95} \leq 2$ as a criterion for uniformly exposed groups, which translates into workers within a uniformly exposed group should have their individual mean exposures within a factor two.

In order to study the interrelationship between long-term trends in average exposure concentration and between- and within-worker variability, smoothing splines were fitted through the geometric mean concentrations respirable dust and respirable quartz and between- and within-worker fold-ranges per combination of site, job, and measurement campaign. The smoothing splines were generated from a generalized additive model using the 'mgcv' package in R (version 3.3.1.) (Wood, 2017).

Results

Respectively 2302 and 2028 "site-job-sampling campaign" groups of workers with repeated respirable dust concentrations and respirable quartz concentrations could be analysed. The median number of workers sampled per group and the number of measurements taken within a group in a campaign were respectively 4 and 8 for respirable dust and 3 and 7 for respirable quartz and stayed stable over time. [Detailed results in terms of descriptive analysis are shown in Table S1 in the Supplementary material (available at Annals of Work Exposures and Health online)].

Table 1 shows estimated median between- and within-worker fold-ranges in respirable dust and respirable quartz concentrations overall and by standardized job. Overall, the median between-worker fold-range was low for both respirable dust and quartz (${}_{B}R_{0.95}$ respectively 1.78 and 1.83). For most jobs fold-ranges in average personal concentrations were within a factor 2 (${}_{B}R_{0.95} < 2$) for both respirable dust and respirable quartz. Only the jobs maintenance worker, multi-skilled worker and plastification worker had median between-worker fold-ranges slightly above a factor 2 for respirable dust. For respirable quartz half of the twelve job categories had a between-worker fold-range above a factor 2: bagging worker (2.09), dry process operator (2.41), maintenance worker (2.01), miller

Table 1. Median geometric mean concentration and within- and between-worker variability by job for respirable dust and respirable quartz

Job[*]	Respirable dust								Respirable quartz							
	G	k	n	GM[a]	${}_{B}S_{g}$ [b]	${}_{B}R_{0.95}$ [c]	${}_{W}S_{g}$ [d]	${}_{W}R_{0.95}$ [e]	G	k	n	GM[a]	${}_{B}S_{g}$ [b]	${}_{B}R_{0.95}$ [c]	${}_{W}S_{g}$ [d]	${}_{W}R_{0.95}$ [e]
All	**2302**	**4**	**8**	**0.20**	1.15	**1.85**	**1.78**	**10.0**	**2028**	**3**	**7**	**0.014**	**1.16**	**1.83**	**2.14**	**21.2**
Bagging worker	286	4	8	0.29	1.00	1.00	1.86	11.4	250	4	8	0.034	1.21	2.09	2.06	17.0
Crusher operator	70	3	7	0.24	1.09	1.31	1.68	7.59	42	3	7	0.020	1.00	1.00	2.01	15.6
Dry process operator	260	3	7	0.20	1.19	1.98	1.76	9.19	235	3	7	0.016	1.25	2.41	2.05	16.7
Foreman	212	3	7	0.09	1.06	1.24	1.66	7.23	190	3	7	0.007	1.00	1.00	2.05	16.7
Laboratory worker	183	3	6	0.13	1.00	1.00	1.78	9.58	164	3	6	0.009	1.10	1.45	1.94	13.5
Maintenance worker	284	4	8	0.24	1.20	2.06	1.87	11.8	235	4	7	0.013	1.19	2.01	2.32	27.2
Miller worker	152	3	7	0.20	1.12	1.54	1.70	8.05	131	3	7	0.024	1.26	2.48	1.89	12.0
Multi-skilled worker	89	4	8	0.20	1.20	2.05	1.70	8.02	77	3	8	0.009	1.27	2.51	2.04	16.4
Plastification worker	24	3	6	0.21	1.45	2.31	1.65	7.07	24	3	6	0.023	1.10	1.47	1.95	13.7
Quarry operator	173	4	10	0.10	1.07	1.29	1.82	10.4	163	4	10	0.005	1.39	3.64	2.40	30.9
Transport worker	390	4	7	0.12	1.09	1.41	1.79	9.75	344	3	7	0.009	1.03	1.14	2.07	17.3
Wet process operator	175	3	7	0.10	1.07	1.31	1.65	7.17	169	3	7	0.008	1.00	1.00	2.07	17.5

G = number of site-job-campaign groups; k = median number of workers per group; n = median number of measurements per group.
[a]GM = geometric mean concentration (mg/m^3).
[b]${}_{B}S_{g}$ = between-worker geometric standard deviation.
[c]${}_{B}R_{0.95}$ = between-worker fold-range in average concentrations.
[d]${}_{W}S_{g}$ = within-worker geometric standard deviation.
[e]${}_{W}R_{0.95}$ = within-worker fold-range in daily concentrations.
[*]Lime hydration operator is excluded from analyses due to limited data (n = 4).

worker (2.48), multi-skilled worker (2.51) and quarry operator (3.64).

Generally, the within-worker variability exceeded the between-worker variability for both respirable dust and respirable quartz. For quartz the median temporal variability was considerably higher than for respirable dust (21.2 versus 10.0). The within-worker variability in respirable dust and respirable quartz exposure concentrations was high for the maintenance worker (11.8 and 27.2, respectively), quarry operator (10.4 and 30.9, respectively) and bagging workers (11.4 and 17.0, respectively).

When we look at the individual estimates for each "site-job-sampling campaign" group of workers it is clear that despite the low overall between-worker variability respectively 44% and 50% of the groups had a between-worker fold-range above 2 for respirable dust and quartz. Respectively 22% and 28% had even between-worker fold-ranges above 10. Extreme day-to-day variability (fold-range above 100) was present for respirable dust and quartz in respectively 8% and 18% of the groups [see Figs. S1 and S2 in Supplementary material (available at Annals of Work Exposures and Health online)].

In Fig. 1a and b the trends in the within- and between-worker fold-ranges in exposure concentrations are shown. From Fig. 1a it becomes clear that the median between-worker variability in respirable dust concentrations was low and further reduced over time. The same phenomenon albeit somewhat less strong was observed for the between-worker fold-ranges for respirable quartz concentrations (Fig. 1b).

The within-worker variability for both exposures showed a much more irregular pattern of decreasing and increasing. In the first years of the Dust Monitoring Programme the within-worker respirable dust exposure variability declined rapidly, from a fold-range of 20 to a fold-range of 10. It stayed at that level till around 2010 and further declined to a lowest fold-range of about 7 in 2012 after which it rapidly increased again to 10 in the most recent years (Fig. 1a). The day-to-day variability for respirable quartz, decreased from a fold-range of 50 to a fold-range of 25 between 2002 and 2006 and remained stable until 2010. Between 2010 and 2014 it declined further to a fold-range of 15 and after that started to increase again to a fold-range of 20 in the most recent years (Fig. 1b).

Overall, the 90th percentiles of the fold-ranges distributions showed that extreme between-worker and within-worker variability steadily declined over time. For respirable quartz this trend was strikingly more steep.

In Fig. 2a and b, the trends in between-worker and within-worker variability are combined with the trends in arithmetic and geometric mean concentrations. The decline in within-worker variability during the first years of the project was reflected in a rapid decline of mean concentrations in those years (GM and AM). Also, the increase in temporal variability seen during certain time periods slowed the decline in average concentrations and even resulted in a temporarily increase in average respirable dust concentrations in the period 2008–2012 and the most recent period 2016–2018. For respirable quartz the interrelationship between exposure variability and mean concentrations was less clear.

Discussion

In this study, we estimated within- and between-worker variability across ad entire industrial sector for almost two decades based on respectively 17 000 shift-long personal respirable dust measurements and 15 000 similar respirable quartz measurements. This allowed insight in temporal trends in variability of respirable dust and respirable quartz concentrations within the European industrial minerals sector over a period of almost 20 years. Long-term trends in between-worker variability were downwards most clearly for respirable dust and at a somewhat slower pace for respirable quartz. The within-worker variability showed a much more irregular pattern after an initial downward trend it increased, decreased, and increased again during the period. Like other industrial sectors the industrial minerals industry was hit by the economic recession (2008–2013) leading to reduction and downsizing of workforces resulting in more diverse tasks and less control due to delayed maintenance (Zilaout *et al*., 2020). So, it seems that the (relative) size of the temporal variability (and consequently the average exposure) is amongst others depending on macro-economic developments and therefore regular measurement campaigns are needed to ascertain compliance to occupational exposure limit values. Our results also indicate that long-term trends in average exposure concentrations and variability in exposure concentrations are interrelated more so for respirable dust than for respirable quartz.

As shown before in multiple studies across industries and exposures (Kromhout *et al*., 1993; Kromhout and Heederik, 1995; Van Tongeren *et al*., 2006; Jones and Burstyn 2016; Symanski *et al*., 2006), within-worker exposure variability outweighs between-worker variability for respirable dust and quartz within this industrial minerals sector. The within-worker variability in exposure concentrations was lower for respirable dust than for respirable quartz. The temporal fold-range by job was two to three times higher for respirable quartz than for respirable dust. Variable percentages of quartz in respirable dust from the minerals worked with, will

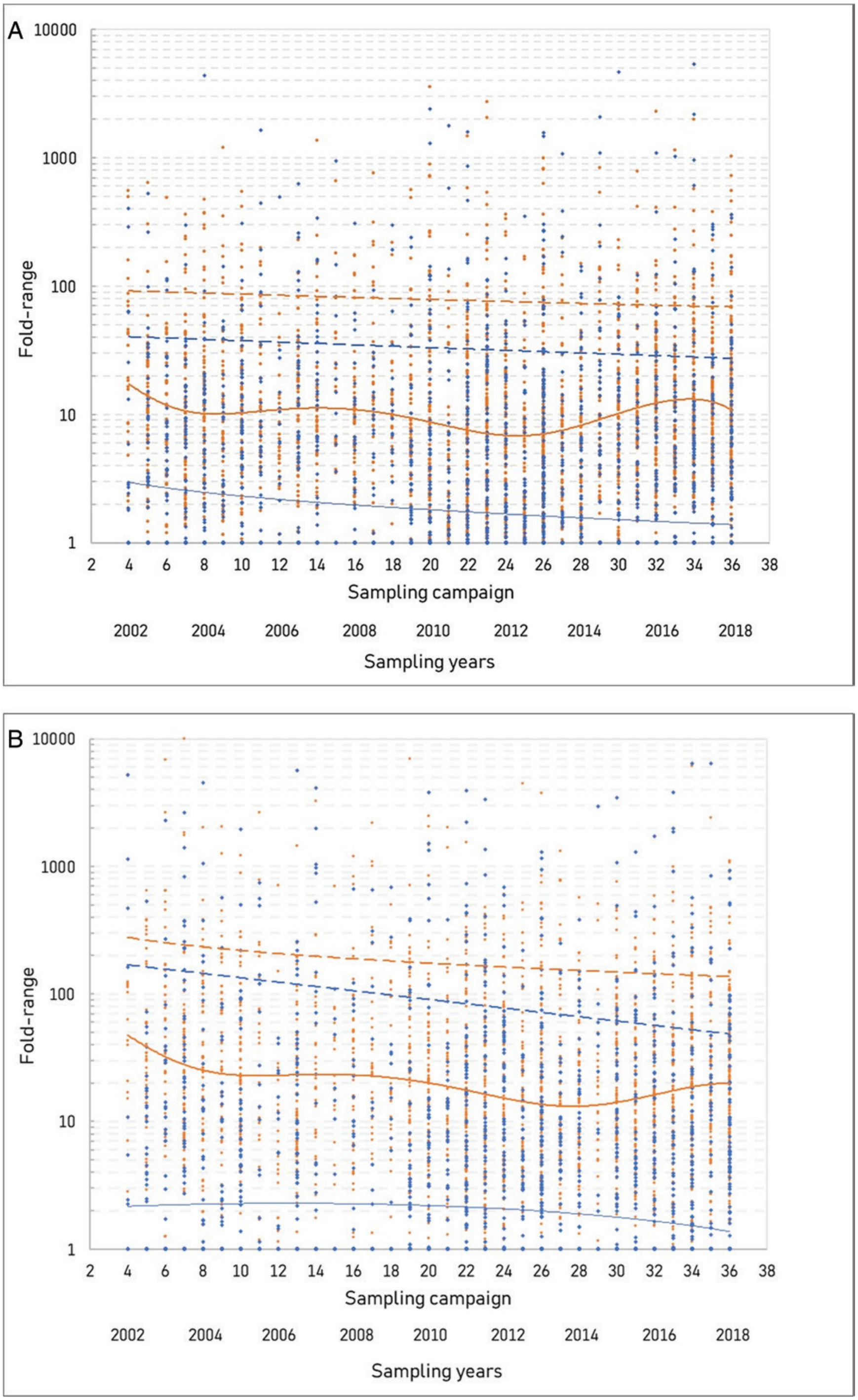
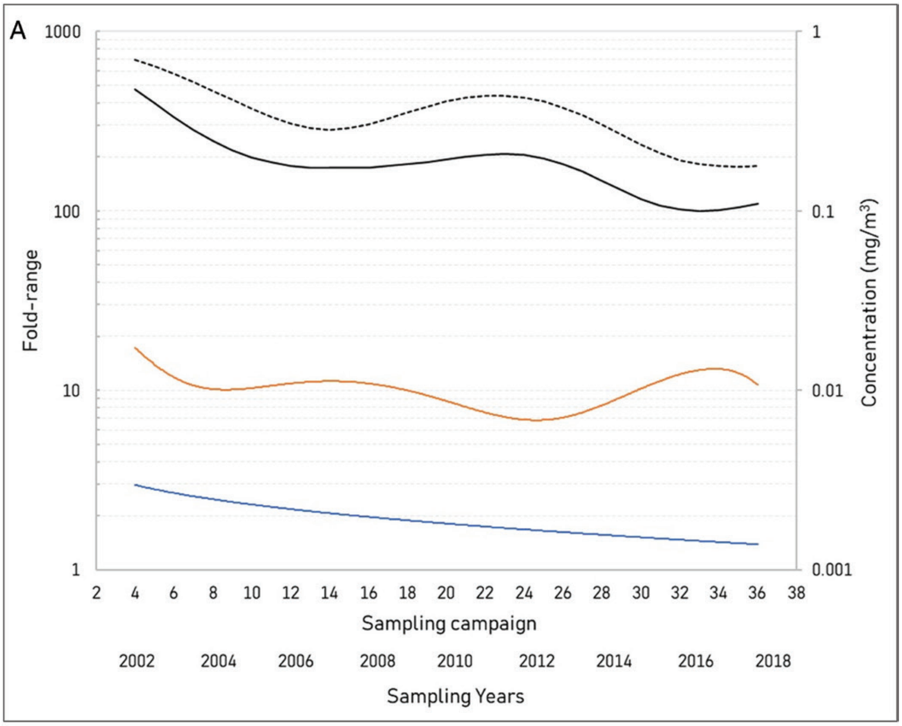


Figure 1 (a) Estimated within-worker (orange dots) and between-worker variability (blue dots) (presented as fold-range) in respirable dust concentrations for 2302 groups of workers performing the same job in a site during a campaign within IMA-DMP: median within-worker variability fold-range (orange line), median between-worker variability fold-range (blue line), 90th percentile "within-worker" variability (orange dotted line) and 90th percentile "between-worker" variability (blue dotted line). (b) Estimated within-worker (orange dots) and between-worker variability (blue dots) (presented as fold-range) in respirable quartz concentrations for 2028 groups of workers performing the same job in a site during a campaign within IMA-DMP: median within-worker variability fold-range (orange line), median between-worker variability fold-range (blue line), 90th percentile "within-worker" variability (orange dotted line) and 90th percentile "between-worker" variability (blue dotted line).



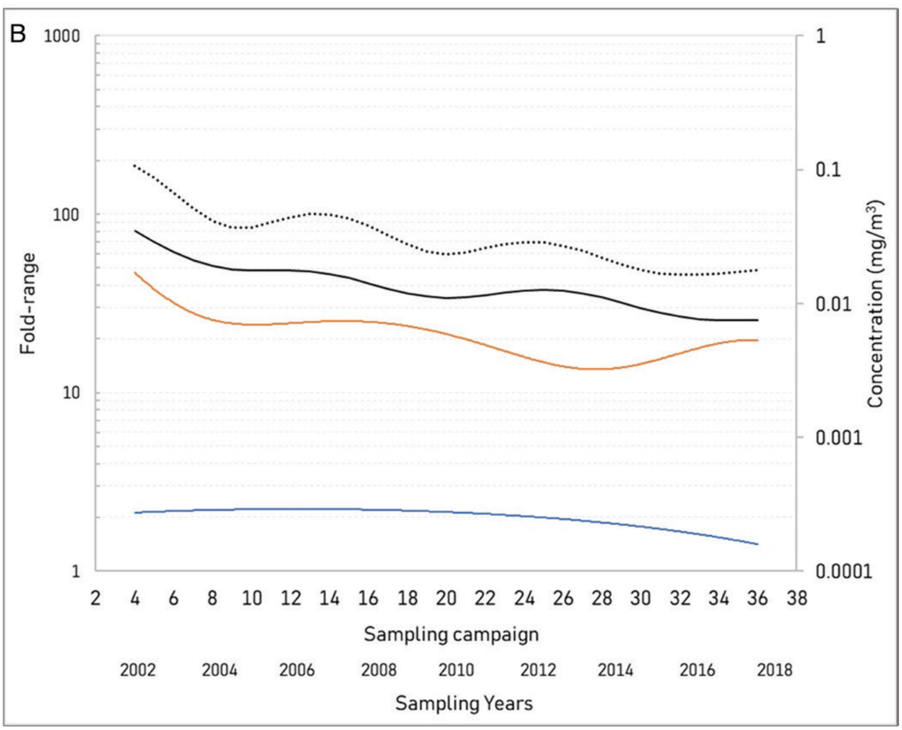


Figure 2 (a) Long-term trends in arithmetic mean respirable dust concentration in mg/m^3 (dotted line), geometric mean respirable dust concentration in mg/m^3 (black line), within-worker variability fold-range (orange line) and between-worker variability fold-range (blue line) for 2302 groups of workers performing the same job in a site during a campaign within IMA-DMP. (b) Long-term trends in arithmetic mean respirable quartz concentration in mg/m^3 (dotted line), geometric mean respirable quartz concentration in mg/m^3 (black line), within-worker variability fold-range (orange line) and between-worker variability fold-range (blue line) for 2028 groups of workers performing the same job in a site during a campaign within IMA-DMP.

be the main underlying reason. In addition, the additional chemical analytical steps to estimate quartz concentrations will have introduced measurement error and consequently further increased exposure variability.

In a previous study it was shown that a greater number of workers and measurements in a group resulted only in higher within-worker variability (Kromhout *et al*., 1993). The median between-worker fold-range reported by Kromhout *et al*. (1993) for particulate exposures was 4 and considerably higher than the median fold-range of 1.8 in our study. The median within-worker fold-range in the across industry study was reported to be 14, which is in between our estimates of 10 and 20 within-worker fold-ranges for respectively respirable dust and quartz.

The reason for our lower between-worker variability might be the result of standardized nomenclature within the IMA-DMP database (Zilaout *et al*., 2020), which showed more than 50% of uniformly exposed groups compared to only 25% of groups defined by job and location reported across industries by Kromhout *et al*. (1993). The decreasing between-worker differences in personal average concentrations over time will most likely be an effect of implementation of control measures and awareness of the crystalline silica hazard among management and workers.

The only other study that reported trends over time in between- and within-worker variability showed a decline in both over a nine-year period (Vermeulen *et al*., 2000). In our study a similar pattern was seen for the between-worker variability, but for the within-worker variability an irregular pattern was apparent that became visible due to frequent monitoring with IMA-DMP.

In our study, the number of groups of workers with extreme day-to-day variability slowly declined over time indicating that more highly variable exposure conditions became better controlled. Moreover, as we reported previously, exposure to respirable dust and respirable quartz showed an overall downward temporal trend (Zilaout *et al*., 2020). Median geometric mean respirable dust and respirable quartz concentrations decreased from 2002 to 2016 roughly four-fold and two-fold, respectively. Due to these downward trends in geometric mean concentrations and an overall lower variability compliance (estimated as probability of exceedance of OELV below 5%) with respectively an OELV of 2 mg/m^3 for respirable dust and 0.1 mg/m^3 for respirable quartz consequently increased dramatically ~35% to ~95% for respirable dust (assuming an OELV of 2 mg/m^3) and from ~15% to ~85% (considering the current European OELV of 0.1 mg/m^3).

This decrease might have been the result of direct feedback to companies to help them identify and intervene in hotspots where exposures were not in compliance resulting in the implementation of (better) control measures, increased awareness of presence and health effects of RCS and resulting changes in behavior during task performances among the involved workers might have played a role as well. Previous work by Basinas *et al*. (2016) showed that direct feedback on measured dust concentrations resulted in lower levels among farmers over time.

Strengths and limitations

An important strength of IMA-DMP is the use of a standardized common protocol under strict quality criteria including a well-defined measurement strategy, regular measurement campaigns and consequently, availability of repeated measurements per worker (Zilaout *et al*., 2020). As Vinzents *et al*. (2001) pointed out direct comparisons of between- and within-worker variances for particulate exposure between various studies are often not possible due to differences in applied measurement strategies and large differences in number of repeated measurements. The IMA-DMP protocol was adhered to by participating companies participating in the IMA-DMP, allowing detailed analyses and comparisons over time providing insights into temporal changes in exposure variability across an entire European industrial sector. Within the IMA-DMP the number of workers per site-job-sampling campaign combination and the number of repeats remained almost constant and this ensured a proper interpretation and comparison of the results over time. In order to investigate temporal changes in variability in other industries, large prospective exposure databases as IMA-DMP should be created. This is particularly essential since variability in exposure concentrations is of utmost importance for risk assessment and regulatory purposes like compliance testing (Rappaport *et al*., 1995), but also for epidemiological studies (Steenland *et al*., 2001; Loomis and Kromhout, 2004). We realize the relatively small number of workers ($k_{\text{resp dust}} = 4$, $k_{\text{resp quartz}} = 3$) and measurements ($n_{\text{resp dust}} = 8$, $n_{\text{resp quartz}} = 7$) within a group of workers with the same job on a site in a sampling campaign will have led to uncertainty in the estimation of the between- and within-worker variability in exposure concentrations. However, given a similar measurement strategy across sites and over the entire time period we expect no bias in the trend estimates of within- and between-worker variability. When IMA-DMP exposure measurements for a group of workers with the same job at a specific site from adjacent measurement campaigns were merged, estimates of between- and within-worker variability appeared to be only marginally different (results not shown). Given the presence of considerable temporal trends in shift-long exposure concentrations pooling across adjacent campaigns would result in non-stationarity of the exposure distributions and therefore to estimate the variance components for exposure data collected within a measurement campaign despite the relatively small datasets.

Conclusion

Within the European industrial minerals sector day-to-day variability predominated the between-worker variability for both respirable dust concentrations and quartz concentrations. The day-to-day variability in concentrations by job was two to three times higher for respirable quartz than for respirable dust. A relatively high percentage of uniformly exposed groups were present and has increased over time. Long-term trends in exposure variability were present, but were clearly different for between- and within-worker exposure variability. The trends for between-worker variability in exposure respirable dust and respirable quartz concentrations were gradually downward over the entire period of almost two decades. In contrast, for the within-worker variability in exposure concentrations clear downward and upward temporal trends were apparent for both respirable dust and respirable quartz.

The (relative) size of the temporal variability (and consequently average exposure concentrations) are by definition related, but in time unpredictable and therefore regular measurement campaigns are needed to ascertain compliance to occupational exposure limit values.

Acknowledgements

We would additionally like to gratefully thank the participating companies and their employees across Europe for their outstanding and long-lasting collaboration.

Funding

The authors gratefully acknowledge the funding of this project by the Industrial Minerals Association Europe (IMA-Europe). IMA-Europe had no involvement in the analysis and interpretation of data, in the writing of this manuscript and the decision to submit the paper for publication.

Conflict of interest

The authors declare no conflict of interest relating to the material presented in this article.

Data Availability

The data underlying this article are not shared publicly to protect the privacy of individuals and organizations that participated in the study. De-identified data may be shared on reasonable request to the data owners (IMA-Europe).

SUPPLEMENTARY DATA

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

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