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Original Article

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Exposure to Particulate Matter and Respirable Crystalline Silica in Tunnel Construction Workers Using Tunnel Boring Machines

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Abstract

Objectives: This study aimed to assess the exposure to a selection of aerosols and gases in the work environment for workers performing tunnel construction using tunnel boring machines (TBMs), to identify determinants of exposure based on the information available and to calculate robust estimates of exposure using a statistical model. The focus was particulate matter (PM) and respirable crystalline silica (RCS). In addition, concentrations of nitrogen dioxide (NO_2), elemental carbon (EC), and oil mist were assessed.

Methods: Personal sampling was conducted from February 2017 to February 2019. PM in the thoracic and the respirable aerosol fractions was collected, and RCS was determined in the respirable aerosol fraction. Context information was collected on questionnaires. Because the workers could participate in the sampling more than once and multiple measurements were performed on the same date a mixed model was used in the analysis. Concentrations of PM and RCS are presented as estimated and measured geometric means (GM_{est} and GM_{mea}) and estimated arithmetic mean (AM_{est}) in addition to the median. Measured concentrations of NO_2, EC, and oil mist are presented as geometric means.

Results: A total of 290 and 289 personal samples of PM in the thoracic and respirable aerosol fractions were available for analysis, respectively. Work title/work location, type of work (production, maintenance, or a combination of the two), and date of sampling were identified as determinants of exposure. Workers in the front of the TBMs had the highest exposure to PM and RCS. The GM_{est} of RCS exposure varied from 35 to 413 µg m^{-3} depending on the work title. The geometric standard deviations for measured RCS concentrations by work title ranged from 1.6 to 3.5. A total of 16 samples of NO_2 and EC and 12 samples of oil mist were collected. Maximum values of NO_2 and EC were 54 µg m^{-3} and 23 µg m^{-3}, respectively. The maximum measured value of oil mist was 0.08 mg m^{-3}.

Conclusions: All TBM workers were exposed to PM and RCS. Exposure to RCS may be substantial, and workers in front of the TBM were exposed to the highest concentrations of both PM and RCS. A day-to-day variation was found, probably caused by differences in drilling activities. Preventive measures are warranted to keep the exposure to PM and consequently the exposure to RCS as low as possible to protect the health of workers in tunnel construction.

Keywords: construction; crystalline silica; dust; personal sampling; quartz; rock dust; TBM

What's Important About This Paper?

This detailed study shows that tunnel construction workers on tunnel boring machines are exposed to particulate matter and respirable crystalline silica. The exposure levels are comparable to previously published exposure levels from studies on workers using the traditional drill and blast method. Preventive measures are important to keep the exposure to crystalline silica as low as possible to protect the health of workers in tunnel construction.

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Introduction

In Norway, the infrastructure is dependent on tunnels, and the drill and blast method has been the common construction method. Previous studies have shown that workers using this method are exposed to aerosols and gases, e.g. particulate matter (PM), crystalline silica (α-quartz), oil mist, and diesel exhaust emissions (Bakke et al., 2001, 2014), in concentrations that may lead to airway inflammation and decline in lung function (Ulvestad et al., 2001a, 2001b; Bakke et al., 2004; Ulvestad et al., 2015).

An alternative method in tunnel construction is to use tunnel boring machines (TBMs). A TBM function as an underground factory excavating and, optionally, mounting tunnel lining at the same time (Yun, 2019). TBMs can run on electricity and come in various constructions and sizes depending on type of project and geological conditions. The main components are a cutter head with numerous cutter discs in the front of the machine, conveyor belts/pipes to remove crushed rock mass from the tunnel, and erectors to install segments to line the tunnel (Yun, 2019). In addition, the TBM can be shielded to enable excavation in geologically challenging areas (Yun, 2019). TBM workers' exposure to respirable dust and respirable elemental carbon was described by Galea et al. (2016). Otherwise, the literature is sparse in the description of TBM workers' exposures and health.

In 2015, the construction of a 20 km long twin rail tunnel using TBMs started in Norway. The National Institute of Occupational Health (STAMI) in Norway initiated a research project to study the exposure and respiratory health among TBM workers. As geological conditions in Norway are dominated by bedrock commonly composed of granite and gneiss, typically containing 20–40% crystalline silica (NGU, 2015), a focus on respirable crystalline silica (RCS) was a natural consequence. Inhalation of RCS may lead to adverse health effects like loss of lung function, silicosis, and lung cancer (IARC, 2012; Leung et al., 2012; Ulvestad et al., 2020).

The aim of the present study was to assess the exposure to a selection of aerosols and gases among tunnel construction workers using TBMs, with a focus on PM and RCS, and to identify determinants of exposure based on the information available. In addition, it was aimed to obtain robust estimates of the exposure to PM and RCS for the whole study period using a statistical model taking the potential determinants of exposure and sources of variability into account.

Methods and materials

Site description

The twin tunnels were excavated using four TBMs, driving in pairs in parallel from the same starting point. Each with a 10 m diameter cutter head, containing cutter discs, mounted on a 150 m long double shielded electricity-driven TBM body. The crushed rock mass from the drilling was transported out of the tunnel on conveyor belts. To reduce the spread of PM from the cutter head area to the other parts of the TBM, water curtains were used. In addition, fresh air from the outside was led to the front of the TBMs through a ventilation system, where the air was blown out of the tunnel, leading the polluted air away from the TBM. The tunnel lining was built using prefabricated concrete segments transported from the outside construction area, mounted, and settled with erectors by the TBM crew as the drilling progressed. The gap between the lining and the rock was filled with cement-based grout delivered to the TBMs as a wet mix through pipes. Diesel-powered vehicles were used for the transport of workers and concrete segments in the tunnels.

Cross passages between the parallel railway tunnels were excavated by other contractors not part of this study, using the drill and blast method. All work related to this was situated some distance behind the TBMs and was not directly affecting exposure on the TBMs.

Sampling organization and strategy

All TBM workers were considered eligible for participation in this study and participation was voluntary. Office workers and administrative personnel were not included in the sampling. Workers were classified based on their work title, which was defined by the contractor, and described in Table 1. A TBM crew consisted of 20–22 workers per shift per TBM. A two-shift scheme was used.

The sampling strategy was set by the STAMI project group and aimed at collecting a representative distribution of samples across work titles and TBMs. The samples described are all collected with personal sampling equipment. An occupational hygienist led the overall organization of the sampling following the sampling strategy. For practical reasons, sampling took place at one TBM for each day of sampling including a maximum of 7 persons, both during production and maintenance work.

Sampling questionnaires including work title, work location on the TBM, time for the start and stop of sampling, pump flow rate, and additional comments were completed at the end of each sampling. General information about the work performed (main type of work, start/stop of drilling, and other specifications about the shift) was also collected.

The exposure assessment started in February 2017 and ended in February 2019. The study was approved by the Ethical Research Committee (REK) of south-east Norway (project number 2016/861).

Table 1. Work titles with corresponding prevalent work location on the tunnel boring machine (TBM), brief description of work tasks and number of samples

Work title	Work location	Work tasks	Number of samples					
			PM$_{\text{thor}}$	PM$_{\text{resp}}$	RCS	NO$_2$	EC	Oil mist
Cutter head mechanic	Cutter head/ front	Changing cutter discs and cleaning in cutter head area.	nm[a]	6	6	nm	nm	nm
Shield worker	Front	Working around the shield. Maintenance and cleaning.	5	5	5	1	1	2
Erector operator	Front	Operating the process of assembly and installation of segments	34	33	33	3	3	2
Segment crane operator	Middle	Move segments from the truck and further to assembly and installation in the segment feeder	35	35	35	2	2	nm
Grouter	Middle	Grouting procedures. Grout is filled into the gap between the concrete segments and the excavated area.	37	37	37	4	4	nm
TBM operator	Middle	Runs the TBM from the control cabin	11	11	11	2	2	nm
Pipe worker	Back	Performing pipe extension and other pipe-related tasks	23	23	23	nm	nm	2
Conveyor	Back	Tasks related to conveyor belt including belt extension.	15	14	14	1	1	2
Welder	All over	Welding all over TBM.	8	8	8	nm	nm	nm
Electrician	All over	Various tasks related to electrical installations on the TBM.	35	30	32	nm	nm	nm
Mechanic	All over	Various tasks all over the TBM	51	53	52	nm	nm	4
Shift boss	All over	Supervising TBM workers	28	27	27	nm	nm	nm
Helper	All over	Workers without specified work title.	8	7	7	3	3	nm
Total			290	289	290	16	16	12

PM$_{\text{thor}}$, particulate matter in the thoracic aerosol fraction; PM$_{\text{resp}}$, particulate matter in the respirable aerosol fraction; RCS, respirable crystalline silica; NO$_2$, nitrogen dioxide; EC, elemental carbon; nm, not measured. [a]Cutter head mechanics carried the equipment for samples in the respirable aerosol fraction only due to the restricted workspace.

Exposure variables

Exposure to PM was measured by personal sampling in two aerosol fractions simultaneously: thoracic aerosol fraction, hereafter called PM in the thoracic aerosol fraction (PM$_{\text{thor}}$), and respirable aerosol fraction, hereafter called PM in the respirable aerosol fraction (PM$_{\text{resp}}$). These aerosol fractions contain particles that penetrate the airways beyond the larynx, reaching the bronchial, and alveolar regions, respectively (CEN, 1993). α-Quartz concentrations were determined in the PM$_{\text{resp}}$ samples and represent the exposure to RCS. Due to the restricted workspace cutter head mechanics carried only the sampling equipment for PM in the respirable aerosol fraction.

From the original exposure variables, the PM$_{\text{resp}}$/PM$_{\text{thor}}$ ratio and the percentage of RCS in PM$_{\text{resp}}$ were calculated in order to study differences in these ratios across work locations and work titles. Additionally, a restricted number of samples of oil mist, nitrogen dioxide (NO$_2$), and elemental carbon (EC) were collected by personal sampling.

Sampling methods

Particulate matter

Particulate matter in the respirable aerosol fraction was collected on 37 mm polyvinyl chloride (PVC) membrane filters with 5 µm pore size (PVC503700, MerckMillipore Corporation, MA, USA). Respirable cyclone samplers (JS Holdings, Stevenage, UK) were used and operated at 2.2 l min^{-1}. PM in the thoracic aerosol fraction was collected on 37 mm PVC membrane filters with 5 µm pore size (PVC503700, MerckMillipore Corporation, MA, USA). Thoracic cyclone samplers (BGI GK 2.69, Mesa Labs, CO, USA) equipped with 37 mm cassettes (M000037A0, MerckMillipore Corporation, MA, USA) operated at a flow rate of 1.6 l min^{-1} were used. Personal sampling pumps (SG5200, GSA Messgerätebau GmbH, Ratingen, Germany) were used. Calibrated rotameters were used to measure the airflow rates through the samplers at the start and end of all samples. All pumps had a function of auto shutdown in case of a decrease in the flow of more than 5%.

Oil mist, elemental carbon, and nitrogen dioxide

Oil mist samples were collected with a 37 mm filter cassette (MerckMillipore, MA, USA) with two filters, as described by Kirkhus et al. (2015). Personal sampling pumps (SG4000ex, GSA Messgerätebau GmbH, Ratingen, Germany) were operated at a flow rate of 1.4 lmin^{-1}.

Combined 25 mm filter cassettes (M000025A0, MerckMillipore, MA, USA) were used to sample EC and NO_2 with methods previously described by Berlinger et al. (2019) and Hovland et al. (2012), respectively. Personal sampling pumps (SG5200, GSA Messgerätebau GmbH, Ratingen, Germany) were operated at a flow rate of 2.0 lmin^{-1}.

Laboratory analysis

PM and respirable crystalline silica

The collected PM mass was determined by weighing all filters before and after exposure using a daily calibrated Sartorius MC 5 balance (Sartorius AG, Göttingen, Germany) in a temperature- and humidity-controlled room (20 ± 1°C and 40 ± 2% R.H.). All weighing was performed after conditioning the filters for at least 3 days in this climate-controlled room. The accuracy and precision of the measurements were assessed by weighing certified reference masses. The limit of detection (LOD) was calculated as three standard deviations (SD) of all blanks for each analytic procedure. The LOD was 0.02 mg per filter.

The α-quartz content in the respirable aerosol fraction was determined by X-ray diffraction, with a Malvern Panalytical X'Pert^3 Powder diffractometer, equipped with a PIXcel^{1D} detector and an Empyrean X-ray tube (Malvern Panalytical B.V., Eindhoven, Netherlands), according to the silver filter method NIOSH Method 7500 (NIOSH, 2003). The LOD (3 SD of blank filters) was 2 μg per filter.

Oil mist, elemental carbon, and nitrogen dioxide

The determination of oil mist levels was performed according to previously described procedures by Kirkhus et al (2015). An FTIR-instrument (Perkin Elmer Spectrum 100 Fourier Transform Infrared Spectrometer, Perkin Elmer Inc., MA, USA) was used to determine oil mist after sonication in an ultrasonic bath. LOD was 0.0034 mg per filter, corresponding to 0.02 mg m^{-3}.

EC was determined by methods described by Berlinger et al. (2019), analyzing the filter using the OC-EC Aerosol Analyzer (Sunset Laboratories, Tigard, OR, USA). LOD was 2 ng per filter.

The filters with NO_2 were extracted with 10 ml Milli-Q-water and further prepared by combining 5 ml sample extract, 2.5 ml NaOH buffer, and 2.5 ml reagent (*N-(1-Naphthyl) ethylene diamine dihydrochloride 0.25 g, Sulfanilamide 5 g, 50 ml HCl 32% dissolved in Milli-Q-water)*. A spectrophotometer (Genesys 30 Visible spectrophotometer, Thermo Scientific, MA, USA) was used to determine NO_2 (as nitrate). The sample concentrations were calculated using an appropriate range nitrite standard curve prepared using solutions dissolved in Milli-Q-water. The LOD was 3 μg per sample.

Data analysis

Samples were excluded if errors in sampling or equipment were found, or if substantial context information was missing. The air concentration of each contaminant was calculated using the sampled mass divided by the air volume calculated from the sampling time and the flow rate. Where information on the flow rate was missing the fixed flow rate was used (NIOSH, 1998).

The distribution of the exposure variables was checked in plots and by calculation of skewness. The distribution of data was considered to be normal when the skewness was between –2 and 2. The distribution of PM_{thor}, PM_{resp}, and RCS all had skewness exceeding 2, thus ln-transformed prior to further analyses.

Measures of central tendency based on the crude sampling results were calculated for each work title and work location and presented as the median and the measured geometric mean (GM_{mea}) with the corresponding geometric standard deviations.

Further, estimated concentrations of PM and RCS for the whole study period were calculated from a statistical model taking potential determinants and time of sampling into account. As several workers contributed to the sampling more than once and up to seven samples were collected at the same time (date), the samples were assumed to have a dependency structure that had to be handled in the analyses. Therefore, mixed model analyses were used, and identity and date were tested as random effects, respectively.

Work title, the identity of TBM (Number (Nos.) 1–4), type of work performed (production, maintenance, a combination of the two or unknown), and work location on TBM (front, middle, back, all over) were tested in the models as fixed effects. The front was defined from the cutter head to the bridge, the middle from the bridge to the end of gantry 7, and the back from gantry 7 to the end of the TBM. The location 'all over' was defined for workers without a main work location. Work titles were categorized in the work locations based on information from the sampling and discussions with the contractor. Thus, work location can be considered as a grouping of the work titles. Type of work performed during sampling was defined by the contractor by what dominated the work shift, e.g. maintenance or production work, or a combination. As the information was not complete, the category 'unknown' was added. The inclusion of variables on model performance was tested using likelihood ratios tests and the models were compared using Akaike's information criterion (AIC). The residuals were visually inspected in Q–Q plots. To estimate the proportion of between-worker variation and between-date variation, intraclass correlation coefficients (ICC) were calculated.

The mixed model with a date as a random effect was used in the estimation of exposure concentrations. The overall lowest exposed work title (TBM operator), the front work location, and production work was chosen as reference groups for the corresponding variable (work title, work location, type of work). The reference groups were tested against the mixed model coefficients in the variable to test for significant differences. Estimated concentrations of PM_{thor}, PM_{resp}, and RCS were calculated using marginal effect estimates from the statistical model by work title. The estimated geometric mean (GM_{est}) was calculated using the marginal effect coefficient back transformed from ln-scale. The estimated arithmetic mean (AM_{est}) was calculated as the exponential to the sum of the marginal effect coefficient and 0.5 $(\sigma_b^2 + \sigma_e^2)$ from the statistical model with σ_b^2 representing the variance for variation within date and σ_e^2 the variance of the residuals (Seixas et al., 1988).

To explore the effect of time on exposure, an additive mixed model for repeated measures was used. This is a generalization of a linear mixed model using a smooth function for a date instead of a linear term. For this model, linear adjustments were done for the work title and identity of TBM and the type of work.

A $P < 0.05$ was considered statistically significant for all statistical analyses. Data analysis was performed in Stata 16 (StataCorp LP, TX, USA) and in R (version 3.5.3), where the R package mgcv (version 1.8–27) was used to perform the additive mixed model analysis.

Final data set and exclusions

A total of 328 and 336 personal samples of PM_{thor} and PM_{resp} were collected, respectively. The content of RCS was determined in all PM_{resp} samples. A total of 30 and 37 samples of PM_{thor} and PM_{resp}, respectively, and associated RCS samples were excluded because of errors in equipment, unknown time for the start and/or stop, and unexposed or missing samples. All RCS samples below LOD were excluded due to errors in sampling equipment. Two sets of samples collected from the same worker were excluded due to concentrations that were highly influential on the statistical models and considered to be caused by personal work patterns and not representative of the work title.

The PM_{resp}/PM_{thor} ratio should under normal conditions be below 1.0, provided that the two samplers have been exposed to the same atmosphere. A cutoff at 50% more PM_{resp} than PM_{thor} was accepted, and sample pairs with PM_{resp}/PM_{thor} ratio above 1.5 were excluded (six sample pairs and the associated RCS samples). In addition, samples with standardized residuals outside ±3 in models were considered as outliers and were excluded (two PM_{thor}, four PM_{resp}, and three RCS samples).

After exclusions, 290 samples of PM_{thor}, 289 samples of PM_{resp}, and 290 samples of RCS were available in the final dataset (Table 1). The number of samples was evenly distributed over TBM 2–4 with 79, 84, and 78 samples, respectively, with fewer samples (53) collected from TBM 1. The samples were distributed over 64 dates, with an average of 4.5 samples pr. Date (min.–max.: 1–7). A total of 219 and 221 workers contributed to the samples (PM_{thor} and PM_{resp}, respectively). The number of samples per worker varied from 1 to 5.

A total of 16 samples of NO_2 and EC and 12 samples of oil mist were collected.

Results

Determinants of exposure

Work title and work location had a significant effect on the model, while the identity of TBM (Nos. 1–4) did not. The type of work was of significance for the model estimating RCS concentrations.

In the mixed model using the date as a random effect, the variation in the samples was larger between the dates of sampling than the variation within the dates for PM_{thor} and RCS, with an ICC of 0.57 and 0.63, respectively. For PM_{resp} the variation between samples from the same date was larger than the variation in the samples between dates, with an ICC of 0.43.

An ICC of 0.03 was found for PM_{thor} in the mixed models using person identity as a random effect. The ICC was close to zero for PM_{resp} and for RCS. Thus, the between-worker variation was small to non-existent when work title and TBM were accounted for.

PM and respirable crystalline silica

Measured and estimated concentrations of PM and RCS are presented by work title in Tables 2 and 3 and by work location in Table 4. For PM_{thor}, the estimated concentration based on all samples presented as GM_{est} was 0.69 mg m^{-3}, while the GM_{est} for PM_{resp} was 0.41 mg m^{-3} (Table 2). The RCS concentration for

Table 2. Concentrations of particulate matter in the thoracic and respirable aerosol fractions presented by work title. Data are presented in mg m^{-3}

Work title	PM in the thoracic aerosol fraction							PM in the respirable aerosol fraction						
	N	Median	GM$_{mea}$ (GSD)	GM$_{est}$	AM$_{est}$	Min.–Max.	*P* value	*N*	Median	GM$_{mea}$ (GSD)	GM$_{est}$	AM$_{est}$	Min.–Max.	*P* value
All	290	0.71	0.71 (1.9)	0.69	0.84	0.04–5.15		289	0.41	0.42 (2.0)	0.41	0.52	0.03–4.60	
Cutter head mechanic	nm	–	–	–	–	–	–	6	1.54	1.24 (2.4)	1.35	1.71	0.35–3.49	<0.001
Shield worker	5	0.91	1.19 (1.6)	1.01	1.25	0.80–2.44	0.001	5	0.80	0.79 (1.9)	0.67	0.85	0.31–1.80	0.005
Erector operator	34	0.77	0.78 (2.1)	0.77	0.95	0.04–3.91	0.001	33	0.51	0.51 (1.9)	0.49	0.62	0.09–2.59	0.01
Segment crane operator	35	0.72	0.69 (1.6)	0.63	0.77	0.18–1.98	0.05	35	0.39	0.38 (1.7)	0.37	0.47	0.11–1.45	0.2
Grouter	37	0.69	0.69 (1.7)	0.65	0.80	0.12–2.20	0.03	37	0.38	0.39 (1.8)	0.38	0.48	0.11–1.33	0.2
TBM operator	11	0.59	0.53 (2.1)	0.46	0.57	0.15–1.74	Ref.	11	0.41	0.33 (2.0)	0.29	0.37	0.12–1.35	Ref.
Pipe worker	23	0.69	0.73 (2.0)	0.71	0.87	0.20–4.35	0.01	23	0.32	0.37 (2.2)	0.37	0.47	0.14–3.27	0.3
Conveyor	15	0.52	0.57 (1.7)	0.51	0.63	0.21–1.64	0.6	14	0.34	0.33 (1.4)	0.28	0.36	0.16–0.55	0.9
Welder	8	1.46	1.33 (1.9)	1.17	1.44	0.32–3.07	<0.001	8	1.12	0.95 (2.0)	0.90	1.14	0.21–1.94	<0.001
Electrician	35	0.60	0.63 (1.6)	0.57	0.70	0.26–2.17	0.2	30	0.34	0.35 (1.9)	0.33	0.42	0.03–1.70	0.6
Mechanic	51	0.70	0.76 (2.1)	0.83	1.02	0.20–5.15	<0.001	53	0.39	0.45 (2.4)	0.48	0.61	0.11–4.60	0.01
Shift boss	28	0.63	0.62 (1.6)	0.62	0.77	0.17–1.60	0.07	27	0.35	0.33 (1.9)	0.34	0.43	0.08–1.20	0.5
Helper	8	0.88	0.84 (1.9)	0.90	1.11	0.44–1.09	0.002	7	0.48	0.47 (1.5)	0.54	0.68	0.26–0.94	0.03

PM, particulate matter; *N*, number; GM$_{mea}$, geometric mean calculated from measured concentrations; GSD, geometric standard deviation, GM$_{est}$, geometric mean calculated from the mixed model adjusted for identity of TBM (Nos.1–4) and date; AM$_{est}$, arithmetic mean calculated from the mixed model adjusted for identity of TBM (Nos. 1–4) and date; Min.-Max., minimum and maximum measured concentrations; *P* value from the test of each work title's coefficient in the mixed model compared to the reference group (TBM operator); nm, not measured.

Table 3. Concentrations of respirable crystalline silica presented for all samples, by work title, and by type of work. Data are presented in µg m^{-3}

	RCS						
	N	Median	GM$_{mea}$ (GSD)	GM$_{est}$	AM$_{est}$	Min.–Max.	*P* value
All samples	290	60	59 (2.8)	58	93	2–1517	-
Work title							
Cutter head mechanic	6	208	194 (2.9)	413	661	55–934	<0.001
Shield worker	5	221	201 (2.5)	110	175	47–523	0.001
Erector operator	33	88	94 (2.6)	77	123	7–768	0.001
Segment crane operator	35	64	62 (2.2)	50	80	14–453	0.1
Grouter	37	74	63 (2.5)	51	82	5–378	0.1
TBM operator	11	52	61 (2.0)	35	56	26–332	Ref.
Pipe worker	23	47	51 (2.6)	46	73	15–1006	0.3
Conveyor	14	60	56 (1.6)	42	66	31–135	0.5
Welder	8	97	72 (2.7)	118	189	8–191	<0.001
Electrician	32	55	45 (3.1)	46	73	3–542	0.3
Mechanic	52	35	45 (3.5)	66	106	2–1517	0.009
Shift boss	27	42	41 (2.4)	48	77	7–216	0.2
Helper	7	84	57 (2.3)	74	119	17–142	0.02
Type of work							
Production	215	67	65 (2.6)	69	111	3–1517	Ref.
Maintenance	56	36	40 (3.4)	29	46	2–934	<0.001
Production/maintenance	4	64	24 (1.7)	22	35	20–295	0.2
Unknown	15	64	76 (2.0)	89	143	33–335	0.6

N, number; GM$_{mea}$, geometric mean calculated from measured concentrations; GSD, geometric standard deviation, GM$_{est}$, geometric mean calculated from the mixed model adjusted for identity of TBM (Nos.1–4), type of work/work title and date; AM$_{est}$, arithmetic mean calculated from the mixed model adjusted for identity of TBM (Nos.1–4), type of work/work title and date; Min.–Max., minimum and maximum measured concentrations; *P* value from the test of each work title's and each category of type of work's coefficients compared to the corresponding reference group (TBM operator and production, respectively).

all samples expressed as GM$_{est}$ was 58 µg m^{-3} (Table 3). For PM, measured concentrations by work title were in general similar to the estimated concentrations (Table 2). For RCS concentrations there were seen differences, with the largest difference for cutter head mechanics (GM$_{mea}$ 194 µg m^{-3} versus GM$_{est}$ 413 µg m^{-3}) (Table 3).

Overall, exposure to PM and RCS was significantly higher for workers in the front of the TBM than for workers in the middle, back, or all over the TBM (Table 4). In addition, the workers with work location in the front of the TBM were found to have the highest percentage of RCS in PM in the respirable fraction compared to the other workers on the TBM (Table 4).

The work titles with the highest exposure to PM$_{thor}$ (all presented measures) were welders and shield workers (Table 2). The highest exposure to PM$_{resp}$ (all presented measures) was seen for the cutter head mechanics, followed by the welders (Table 2). The cutter head mechanics and the other work titles in the front of the TBM also had the highest exposure to RCS for all presented measures of central tendency, in addition to the welders (Table 3). For the type of work performed, significantly lower concentrations of RCS were found for maintenance work compared to production work (Table 3).

There were no significant differences in PM$_{resp}$/PM$_{thor}$ ratio between samples collected at the front of the TBM and samples from the middle, back, or all over the TBM (Table 4). The exposure to PM and RCS was similar on the four TBMs (Supplementaty Table 1).

The effect of time on the variation in the RCS concentration is illustrated by a *U*-shaped curve in Fig. 1. Borderline significant positive effects were observed at the beginning and at the end of the study period, while significantly lower RCS concentration was observed in the middle of the study period (Fig. 1). Curves with similar tendencies were seen for PM$_{thor}$ and PM$_{resp}$ (not shown).

Table 4. Concentrations of particulate matter in the thoracic and respirable aerosol fractions (in mg m^{-3}), respirable crystalline silica (in µg m^{-3}), the ratio of particulate matter in the respirable and thoracic aerosol fractions and percentage of respirable crystalline silica in the respirable aerosol fraction presented by work location on the TBM

		Work location on the TBM				
		All	**Front**	**Middle**	**Back**	**All over**
PM_{thor}	*N*	290	44	83	41	122
	Median	0.71	0.92	0.69	0.59	0.70
	GM_{mea} (GSD)	0.71 (1.9)	0.87 (2.1)	0.67 (1.7)	0.66 (1.9)	0.70 (1.8)
	GM_{est}	0.69	0.86	0.64	0.65	0.70
	AM_{est}	0.85	1.05	0.79	0.80	0.86
	Min.–Max.	0.04–5.15	0.04–3.91	0.12–2.20	0.20–4.35	0.17–5.15
	P value	–	Ref.	0.001	0.006	0.019
PM_{resp}	*N*	289	49	83	40	117
	Median	0.41	0.57	0.39	0.34	0.39
	GM_{mea} (GSD)	0.42 (2.0)	0.62 (2.0)	0.38 (1.8)	0.36 (1.9)	0.41 (2.2)
	GM_{est}	0.42	0.60	0.39	0.36	0.40
	AM_{est}	0.54	0.77	0.50	0.46	0.52
	Min.–Max.	0.03–4.60	0.09–3.49	0.11–1.45	0.14–3.27	0.03–4.60
	P value	–	Ref.	<0.001	<0.001	<0.001
PM_{resp}/PM_{thor} ratio	*N*	279	42	81	40	116
	Median	0.59	0.64	0.60	0.57	0.58
	AM_{mea} (SD)	0.60 (0.2)	0.61 (0.2)	0.59 (0.2)	0.56 (0.2)	0.60 (0.2)
	AM_{est}	0.60	0.60	0.60	0.56	0.60
	Min.–Max.	0.02–1.46	0.19–0.92	0.10–1.09	0.18–0.97	0.02–1.46
	P value	–	Ref.	0.9	0.4	0.9
RCS	*N*	290	49	83	40	118
	Median	60	114	64	56	45
	GM_{mea} (GSD)	59 (2.8)	113 (2.6)	62 (2.3)	55 (2.2)	44 (3.0)
	GM_{est}	58	101	53	48	52
	AM_{est}	92	163	86	78	83
	Min.–Max.	2–1517	7–934	5–453	15–1006	2–1517
	P value	–	Ref.	<0.001	<0.001	<0.001
% RCS in PM_{resp}	*N*	288	49	83	40	116
	Median	15.7	18.6	17.1	16.6	13.3
	AM_{mea} (SD)	16.5 (7.7)	19.9 (7.7)	17.9 (6.9)	17.1 (7.1)	13.9 (7.6)
	AM_{est}	16.6	19.2	16.0	16.2	16.0
	Min.–Max.	1.3–36.9	6.8–36.0	2.6–34.6	1.3–30.8	1.6–36.9
	P value	–	Ref.	<0.001	<0.001	<0.001

TBM, tunnel boring machine; PM_{thor}, particulate matter in the thoracic aerosol fraction; PM_{resp}, particulate matter in the respirable aerosol fraction; RCS, respirable crystalline silica; *N*, number; GM_{mea}, geometric mean calculated from measured concentrations; GSD, geometric standard deviation; AM_{mea}, arithmetic mean calculated from measured concentrations; SD, standard deviation; GM_{est}, geometric mean calculated from the mixed model adjusted for identity of TBM (Nos. 1–4) date and type of work (RCS only); AM_{est}, arithmetic mean calculated from the mixed model adjusted for identity of TBM (Nos. 1–4), date and type of work (RCS only); Min.–Max., minimum and maximum measured concentrations; *P* value from the test of each work location's coefficient compared to the reference (Front).

Nitrogen dioxide, elemental carbon, and oil mist

The GM_{mea} for NO_2 and EC were 26 µg m^{-3} (max. value 54 µg m^{-3}) and 7.2 µg m^{-3} (max. value 23 µg m^{-3}), respectively. For oil mist, three of 12 samples were above the LOD (0.02 mg m^{-3}). These samples were from two mechanics (0.05 mg m^{-3} and 0.08 mg m^{-3}, respectively) and one segment crane operator (0.04 mg m^{-3}).

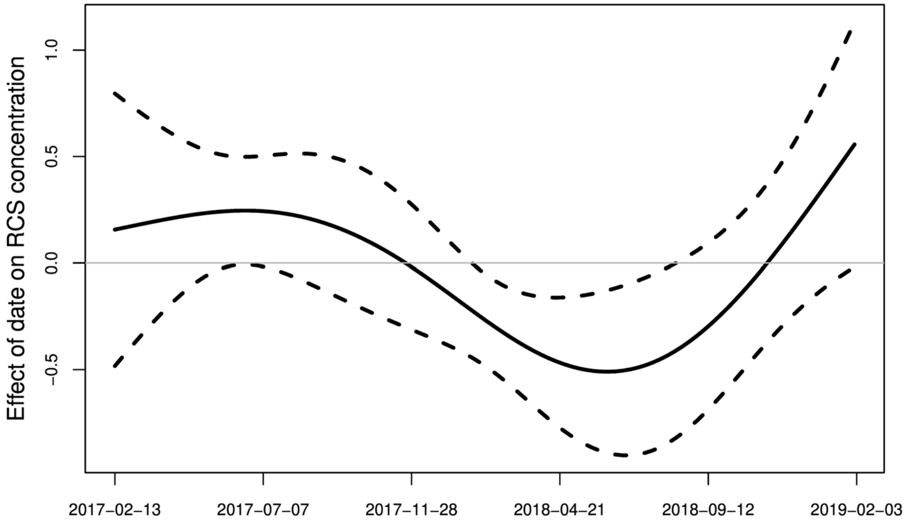

Figure 1. The effect of date on the concentration of respirable crystalline silica (RCS) (ln-transformed) adjusted for number of tunnel boring machine (TBM), work title, and type of work performed (0 = no effect). The bold line represents the estimated mean effect of date on the exposure level. The black dashed lines represent the 95 % confidence interval. Date on the *x*-axis. Effect on the *y*-axis.

Discussion

This study assessed exposure to PM in the thoracic and respirable aerosol fractions and RCS over a 2-year period in a tunnel construction project where four TBMs excavated a 20 km long twin rail tunnel in Norway. To the best of our knowledge, an exposure assessment of this magnitude has not been performed for this type of tunnel construction operation previously. The exposure information from this study will be used in future epidemiological studies to study respiratory health in TBM workers.

As described the workers in front of the TBM were the highest exposed to PM and RCS concentrations. However, all workers on the TBM were exposed to both PM and RCS, and except for higher concentrations in the front compared to the rest of the TBM, the concentrations were rather similar regardless of work location, suggesting that the most important determinant of exposure is to be working on the TBM. The estimated GM for RCS by work location was in the range 52–101 µg m^{-3}, and all work titles had maximum measured concentrations above 100 µg m^{-3}. For comparison, Ulvestad et al. reported a reduction in lung function at a cumulative exposure of 0.08 mg m^{-3} (80 µg m^{-3}) for 21.7 exposure years (Ulvestad et al., 2020).

In 2001, Bakke et al. reported higher exposure to PM_{resp} (GM 0.91 mg m^{-3}) and lower exposure to RCS (GM 0.025 mg m^{-3}) for drill and blast crew compared to the present study. The reported concentrations of NO_2, with a GM of 0.5 ppm, corresponding to 940 µg m^{-3}, were above the concentrations found in the present study (Bakke et al., 2001). In 2014, another study by Bakke et al. reported concentrations more similar to the results from the present study, with a GM of 0.56 mg m^{-3} for PM_{thor} and 63 µg m^{-3} for RCS in tunnel construction using drill and blast. As in the study from 2001, the concentrations of NO_2 (GM 120 µg m^{-3}) and EC (GM 35.2 µg m^{-3}) were higher than what is reported in the present study (Bakke et al., 2014). This is not surprising as the use of diesel-powered vehicles and explosives are sources of NO_2 in the drill and blast method, while the NO_2 sources were limited in the present study on the TBM method. The same was observed for oil mist, with only three samples above LOD in the present study with a maximum value of 0.08 mg m^{-3}, compared to GMs of 0.33 and 0.21 mg m^{-3} in the studies from Bakke et al. (2001) and Bakke et al. (2014), respectively.

Previous studies have to a limited degree reported specifically on exposure among tunnel construction workers on TBMs and comprehensive studies are lacking. Galea et al. reported results comparable to the present study with a GM for PM_{resp} at 0.54 mg m^{-3} for the TBM crew based on 36 personal samples but did not report on RCS concentrations (2016). Bakke et al. reported a GM for PM_{resp} at 2.0 mg m^{-3} and a GM for RCS at 0.39 mg m^{-3} (2001). Compared to the present study, this is more than four times the GM for PM_{resp}, while the RCS concentrations are also considerably higher. In the study by Bakke et al., the TBM crews were generally exposed to higher PM and RCS concentrations compared to drill and blast crews (2001) while building a power plant tunnel. It is assumed that a TBM without shields and with smaller dimensions than in the present study was used. One may speculate that tunnels with smaller cross-sections will have less effective ventilation and that exposure consequently can be higher. As the study by Bakke et al. was performed 20 years ago, one can presume that technical improvements have been implemented on the TBMs since then, reducing the exposure to PM and consequently RCS, but thorough exposure assessments are warranted to ascertain healthy work environments. The present study and previous studies mentioned above had no focus on specific work tasks performed during each sampling. This could be an aim in further research to increase the knowledge about the various work operations' contribution to the variability of the total exposure.

In the present study estimated concentrations calculated from the statistical models represent the overall exposure concentrations for the various work titles and work locations for the whole study period with day-to-day variation, the identity of TBM, and the type of work performed (RCS only) accounted for. These are more accurate descriptions of the overall exposure during the study period than the crude, measured concentrations.

The estimated concentrations were, in general, close to the measured concentrations. The largest differences were seen for the RCS concentrations among cutter head mechanics, shield workers, welders, and helpers. There were few samples from all these work titles, making estimations less certain. In addition, work patterns for cutter head mechanics were not well assessed regarding potential work tasks with peak exposure in limited time intervals and this may not be accounted for in the statistical model. These workers may have high exposures for a limited time, and lower exposure during excavation, as their work tasks in the cutter head are done in maintenance periods. Helpers were a diverse group of workers who probably had more variation in work tasks between dates and TBMs than the workers with defined work titles. As for welders, this work title has group-specific exposures confounding the model as some of the PM measured are due to welding fume and not PM from drilling activities.

Because of dependency on the data, mixed models were used in the statistical analyses. A mixed model with person identity as a random effect did not explain the variation in the exposure. The reason for this is assumed to be that the exposure primarily came from the drilling, and not from personal working patterns. The similar exposure across TBMs is also in favour of this argument. Using the date as a random effect showed that 43–63% of the total variation was explained by variation between dates, depending on the exposure outcome (ICC 0.43 for PM_{resp}, 0.57 for PM_{thor}, and 0.63 for RCS), indicating that exposure at a given time for workers on the same date was correlated and probably conditioned on the state of production activity (drill—no drill, maintenance stops, speed of drilling). Data on production start and stop on each shift was not complete and consequently, this is a source of unexplained variation seen in the variation between dates. For RCS concentrations, variation between dates of sampling was reduced by including the type of work performed as a fixed variable in the mixed model, showing lower RCS concentrations during maintenance work than during production work. Further, geological conditions (e.g. hardness of rock, proportion of crystalline silica in the excavated area) may have influenced exposure at a given time, contributing to the variation between dates. The variation between dates was greater for RCS than for PM in the respirable aerosol fraction, ICC 0.63 vs 0.43, respectively. As RCS was determined in samples of PM_{resp}, this indicates a variation in the proportion of crystalline silica in the bedrock, and consequently, the percentage of RCS in PM_{resp} varied accordingly. The concentration of RCS is dependent on local crystalline silica content in the bedrock and the concentration of PM, both with a linear dependency, and consequently a reduction in PM concentration will reduce the exposure to RCS among TBM workers.

A gradient in PM concentrations was expected with the highest concentrations close to the cutter head (front of TBM) and this was confirmed in the statistical analyses. The same was seen for the percentage of RCS in PM_{resp}, with a significant higher percentage of RCS for the workers in front of the TBM. The gradient in PM concentrations from the front to the back of the TBM was expected to be greater for PM_{thor}, as PM in this aerosol fraction settle faster than the smaller particles in the respirable aerosol fraction, but the statistical analysis did not confirm this. However, no samples of PM_{thor} were performed for cutter head mechanics due to their restricted workspace in the front of the TBM, reducing the number of samples from the front of the TBM with a PM_{resp}/PM_{thor} ratio available for analysis.

The contractor and the builder were provided with results from the sampling regularly. It should be noted that the previous Norwegian OEL for RCS at 0.1 mg m^{-3} still applied during the study period, 2017–2019 (Arbeidstilsynet, 2021) and was used as a target in exposure-reducing strategies.

The first results were presented after 3–4 months of sampling. Because concentrations of RCS were above their expected levels, exposure-reducing measures were implemented (see Supplementary Table S2). There is a lack of details on the time of implementation of preventive measures, but it is considered likely that the negative effect of time on the RCS concentration is a consequence of the implemented engineer-based measures, such as reduced cutter head speed and improved water curtain function. Towards the end of the study period, there was a shift, and one may speculate that the increased effect of date is explained by an increased speed of drilling due to time limitations (not confirmed by the contractor) and increased content of crystalline silica in the bedrock. Regarding personal protection equipment, there was to the best of our knowledge no systematic use of respiratory masks. There were masks available, and the workers were recommended to use them. There was no information on systematic use in the sampling questionnaires.

Strengths and limitations

The strength of this study is the number of samples collected and the long duration of the study period. A full exposure assessment of this size is seldom performed due to the extensive resource consumption.

Due to limited resources, sampling was done when there was manpower to manage the sampling equipment and availability of participants. In addition, there was limited information on possible determinants of exposure when the study was planned, which led to a limited ability to study specific determinants further, leaving work titles as the main information for modelling purposes.

Furthermore, reporting of flow rate was often missing. However, the pumps had auto shutdown which activates in case of flow reductions to less than 95% of the nominal value, reducing the potential bias from missing flow rate on the measurement of PM and RCS.

Diesel exhaust emission components and oil mist were sampled towards the end of the study period, and on one TBM only. Preferably, the sampling had been performed on all TBMs over a longer period. However, as potential sources of diesel exhaust emissions and oil mist were few, there are no indications that the samples are not representable for the exposure on the TBMs.

Conclusions

All TBM workers in this study were exposed to PM and RCS. Exposure to RCS may be substantial, and workers in front of the TBM had the highest exposure to PM and RCS. The observed day-to-day variation is assumed to be caused by differences in drilling activities not uncovered in the present study. Preventive measures are warranted to keep the exposure to PM and consequently the exposure to RCS as low as possible to protect the health of workers in tunnel construction.

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Conflict of interest

The authors declare no conflict of interest relating to the material presented in this article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

Data availability

The data underlying this article cannot be shared publicly due to the privacy of individuals that participated in the study. The data will be shared on reasonable request with the corresponding author.

Supplementary Data

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

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