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Characterization of Occupational Exposure to Air Contaminants in Modern Tunnelling Operations

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ABSTRACT

Objectives: Personal air measurements of aerosols and gases among tunnel construction workers were performed as part of a 11-day follow-up study on the relationship between exposure to aerosols and gases and cardiovascular and respiratory effects.

Methods: Ninety tunnel construction workers employed at 11 available construction sites participated in the exposure study. The workers were divided into seven job groups according to tasks performed. Exposure measurements were carried out on 2 consecutive working days prior to the day of health examination. Summary statistics were computed using maximum likelihood estimation (MLE), and the procedure NLMIXED and LIFEREG in SAS was used to perform MLE for repeated measures data subject to left censoring and for calculation of within- and between-worker variance components.

Results: The geometric mean (GM) air concentrations for the thoracic mass aerosol sub-fraction, α-quartz, oil mist, organic carbon (OC), and elemental carbon (EC) for all workers were 561, 63, 210, 146, and 35.2 μg m^{-3}, respectively. Statistical differences of air concentrations between job groups were observed for all contaminants, except for OC, EC, and ammonia ($P > 0.05$). The shaft drillers, injection workers, and shotcreting operators were exposed to the highest GM levels of thoracic dust (7061, 1087, and 865 μg m^{-3}, respectively). The shaft drillers and the support workers were exposed to the highest GM levels of α-quartz (GM = 844 and 118 μg m^{-3}, respectively). Overall, the exposure to nitrogen dioxide and ammonia was low (GM = 120 and 251 μg m^{-3}, respectively).

Conclusions: Findings from this study show significant differences between job groups with shaft drilling as the highest exposed job to air concentrations for all measured contaminants. Technical interventions in this job should be implemented to reduce exposure levels. Overall, diesel exhaust air concentrations seem to be lower than previously assessed (as EC).

KEYWORDS: aerosols; diesel exhaust; dust; exposure assessment; gases; quartz; thoracic; tunnel

INTRODUCTION

Tunnels in Norway are mainly constructed for road and railway systems and for water supply to hydroelectric power plants. Studies as early as in the 1960s revealed that tunnel construction workers are exposed to aerosols and gases while operating drilling machines and through detonation of explosives in confined spaces (Burns *et al.*, 1962). In addition to particulate matter, diesel exhaust, α-quartz, nitrogen dioxide (NO_2), ammonia (NH_3), oil mist, and oil vapour are air contaminants that dominate in tunnel construction work (Blute *et al.*, 1999; Bakke *et al.*, 2001a; Lewné *et al.*, 2007). Associated health effects include airway inflammation, lung function decline, and chronic obstructive pulmonary disease (Ulvestad *et al.*, 2000; Bakke *et al.*, 2001b; Ulvestad *et al.*, 2001a,b; Bakke *et al.*, 2002; Arcangeli *et al.*, 2004; Oliver and Miracle-McMahill, 2006). A previous study of tunnel construction workers found increased blood concentrations of interleukin-6 and fibrinogen after exposure to respirable dust during a work shift, indicating increased systemic inflammation (Hilt *et al.*, 2002). Furthermore, recently the International Agency for Research on Cancer (IARC) classified diesel engine exhaust as a group 1 human carcinogen, based on sufficient evidence that exposure is associated with an increased risk for lung cancer (Benbrahim-Tallaa *et al.*, 2012). Despite the examples cited above on the topic exposure and health effects of tunnel construction workers, little research has focused on the characterization of exposure to airborne contaminants.

During the last decade, efforts have been made to reduce occupational exposure to aerosols and gases among tunnel construction workers through careful planning of the work and improved ventilation of the tunnels. Today most construction projects use emulsion explosives because of its higher resistance to water. Such explosives have been shown to generate less gases following detonation compared with the former first choice Ammonium Nitrate Fuel Oil explosive (Bakke *et al.*, 2001b). Electrically powered drilling equipment and machines are preferred to reduce the emission of diesel exhaust. In addition, new technologies such as diesel exhaust particulate filters and catalytic converters have been implemented in this industry. Also, there has been focus on use of personal respirators when performing known high-risk tasks such as spraying of mineral oil and wet concrete. Tunnel construction is, however, increasingly mechanized, with extensive use of self-moving units for all processes. Demands for reducing the construction time increases the number of parallel activities and amount of traffic movements within the tunnel. This may introduce new risks for the workers.

The aim of this study was to characterize and assess exposure to aerosols and gases among tunnel construction workers in modern tunnelling operations as part of a 11-day follow-up study on the relationship between exposure to aerosols and gases and possible cardiovascular and respiratory effects in tunnel construction workers.

MATERIALS AND METHODS

Work characteristics

These tunnel construction workers work 12 days consecutively and are then off for 9 days. A typical work shift lasts 10–12 h and includes two breaks of 30 min each. Tunnel construction workers are engaged in rock drilling, charging of explosives, and various support- and finishing work. Occupational job groups included in this study are described in Table 1. Briefly, the excavation process starts off with drilling and charging of explosives. After blasting, the rock is loaded and transported out of the tunnel using dump trucks. Finally, removing of loose rocks using a scalar and various types of rock support is carried out. Rock support includes, e.g. fastening of unsafe rock with steel bolts and sealing of the rock by spraying wet concrete onto the excavated surface. Other important tasks during excavation are mounting ventilation ducts, maintenance and repair of machines, and installation of electrical power supply. If the risk of water leakage into the tunnel is considered high, injection workers carry out rock consolidation with micro concrete to prevent leakage. Up to 25 tons of concrete may be injected during one work shift in holes that can be 22 m deep and cover the entire excavated profile. All tunnels investigated in this study had forced ventilation systems using fans and ventilation ductings to dilute aerosols and gases for workers in all areas of the tunnel. Excavation of the shaft followed the same sequence as for tunnels, however, instead of using an underground drilling rig, pneumatic handheld equipment for rock drilling and a raise climber were used. The only ventilation in the shaft was from pressurized air used to power the drills.

Table 1. Description of job groups included in the study

Job groups	Job specifications	Exposure sources (agents)
Drill and blast workers	A drill and blast operator works mainly at the advancing tunnel face and is specialized in operating a drill jumbo for drilling of blast holes and in charging of explosives. After blasting, the workers also do rock scaling using machines to prevent rock falls.	Transport operations, rock drilling, scaling (particles) Diesel engines (diesel exhaust) Explosives (blasting fumes: nitrogen dioxide, ammonia, particles, volatile organic compounds) Drilling (oil mist/oil vapour)
Drill and blast mechanics	A drill and blast mechanic carries out the majority of his work in small excavated spaces (niches) inside the tunnel. Usually there is no separate ventilation ducting into the work area. A drill and blast mechanic is specialized in repairing equipment and machinery that are used in the excavation process.	Transport operations, rock drilling (particles) Diesel engines (diesel exhaust) Explosives (blasting fumes: nitrogen dioxide, ammonia, particles)
Support workers	Support work is usually performed about 100 m from the advancing tunnel face. Typically work tasks performed by a support worker include installation of drainage pipes and basins, road substructure and roadway, permanent rock support such as rock bolting, water shielding, and frost insulation, cable ducts, and lightening.	Transport operations, rock drilling (particles) Diesel engines (diesel exhaust) Explosives (blasting fumes: nitrogen dioxide, ammonia, particles, volatile organic compounds)
Loaders	A loader is responsible for mucking out crushed rock at the tunnel face. The muck pile is sprayed with water to reduce dust exposure.	Transport operations, loading (particles) Diesel engines (diesel exhaust)
Injection workers	Difficult ground conditions may sometimes give water leakage into the tunnels. In such situations injection workers inject microcement grout into drill holes. The microcement is mixed onsite or offsite.	Transport operations, rock drilling, mixing of cement (particles) Diesel engines (diesel exhaust)
Shotcreting operators	After ventilation of blasting fumes and cleaning of the tunnel face with water, the shotcreting operator sprays wet concrete onto tunnel walls. The concrete is dispersed through a nozzle under high pressure, which generates large amounts of dust. Mineral oil is sprayed onto machinery to prevent sticking of concrete. The concrete is mixed offsite.	Shotcreting (particles) Concrete delivery machine, concrete spray rig (diesel exhaust) Spraying of mineral oil (oil mist/oil vapour)
Shaft drillers	A shaft driller is specialized in drilling shafts. Drilling is done from a working platform of a raise climber by using handheld drilling equipment. The platform is tailored to fit the size and shape of the shaft. Blasting is triggered from a location at the bottom station. Dust and gases created by the blast are cleared by spraying a mixture of water and air through pipes in the guide rail. When the air has been cleared, the crew ascends in the raise climber to the face to scale and install new guide rail section. The drill cycle is similar as for drill and blast workers.	Pneumatic drilling equipment (oil mist/oil vapour, particles) Explosives (blasting fumes: nitrogen dioxide, ammonia, particles, volatile organic compounds)

Study design

All tunnel construction workers (n = 91) employed at 11 available tunnel construction sites located at different parts of Norway were invited for this study in 2010–2011. Participation was voluntarily. One worker decided not to participate. Health effects assessments were performed shortly before the work shift on the first day back on site after 9 days off. After 11 days of work, the medical tests were performed again at the same time of the day.

The workers were stratified into job groups according to tasks performed. Job groups included in this study were drill and blast workers, drill and blast mechanics (a subgroup of the drill and blast workers), support workers, loaders (a subgroup of support workers), injection workers, shotcreting operators, and shaft drillers. Personal air measurements were carried out on 2 consecutive working days prior to the day of the second health examination. Each worker was sampled twice to assess between-worker (BW) and within-worker (WW) variabilities. Thoracic dust, elemental carbon (EC), organic carbon (OC), α-quartz, and NO_2 were measured in all workers. Oil mist, oil vapour, and NH_3 were measured in a subsample of workers from all job groups (N = 57), except shotcreting operators and injection workers. All samples were collected in the breathing zone outside personal protective respirators. To ensure that the exposure level was effectively measured, an attempt was made to sample for at least 7–8 h. Exceptions to this were when workers did particular jobs (e.g. shaft drilling and shotcreting) because overloading of the sampling filters was anticipated. In these situations, the sampling time was reduced. Alternatively, when work activities were less than anticipated due to irregularities of the work operations and unplanned delays, sampling equipment was carried for longer durations.

The sampling time varied between 270 and 855 min [arithmetic mean (AM) = 569 min].

Sampling methods

The thoracic aerosol mass sub-fraction was collected with a thoracic cyclone (BGI GK 2.69 sampler, BGI Inc., MA, USA) operated at a flow rate of 1.6 l min^{-1}. The thoracic fraction is defined by a penetration curve of the total aerosol with a 50% cut-off at an aerodynamic diameter of 10 μm and geometric standard deviation (GSD) of 1.5 (CEN, 1993). Filters were polyvinyl chloride membrane with pore size 5 μm (PVC502500, Millipore Corporation, MA, USA) and a sodium iodide impregnated gas filter pad (cellulose support pad) placed after the aerosol filter by inserting an extra ring into the standard three-part 37-mm aerosol filter cassette (Millipore, MA, USA). The impregnated filter was inserted into the filter cassette to simultaneously collect NO_2 (Hovland *et al.*, 2012).

EC and OC containing particles were collected on pre-cleaned quartz filters (Pallflex Tissue quartz 2500QAT-UP, Pall Corporation, Port Washington, NY, USA) using a 37-mm standard, three-part aerosol filter cassette (Millipore, MA, USA). The sampling flow rate was 2.0 l min^{-1}. Filter cassettes were purchased from Sunset Laboratory Inc. (Tigard, OR, USA). The personal air sampling pumps employed were in-house constructed at the National Institute of Occupational Health (Oslo, Norway) (NIOH) and operated at constant air flow rates through the filters.

Using a combination of 37-mm standard, three-part aerosol filter cassette (Millipore, MA, USA) equipped with a glass filter (No. 1820-037, Whatman GF, Madistone, UK) on top of a cellulose acetate filter (AAWP03700, Whatman GF, Madistone, UK) and tubes containing 150 mg charcoal (100 mg in front section) (No. 226-01, SKC, Blandford Forum, Dorset, UK) mounted in series during sampling, oil mist and oil vapour were collected, respectively (Galea *et al.*, 2012). Personal air sampling pumps (type 224-PCTX4, SKC, Eighty Four, PA, USA) were used to collect samples within a maximum time window of 2 h at an air flow rate of 1.4 l min^{-1}.

Calibrated rotameters were used both at the beginning and at the end of each sampling period to measure the air flow rates through the filters. Samples with >10% decrease in air flow rate over the sampling period were rejected.

Air concentrations of NO_2 and NH_3 were measured with portable direct-reading electrochemical sensors with data logging built into the instruments (PAC7000 Dräger AK, Lübeck, Germany). An averaging period of one reading every 30 s as logging interval was selected. The limit of detection (LOD) for NO_2 and NH_3 were 376 and 1393 μg m^{-3}, respectively. The response factors of the electrochemical sensors were calibrated when the data were downloaded (i.e. about every month) with certified calibration gases (Yara Praxair ASA, Oslo, Norway).

Gravimetric measurement of aerosol mass

The masses of thoracic cyclone filters were measured gravimetrically using a Sartorius AG, MC 210p laboratory micro balance (Göttingen, Germany). The LOD (3 × standard deviation of field blank filters) was 3 µg (31 µg m^{-3} based on 8 h of sampling at a flow rate of 1.6 l min^{-1}). The gravimetric measurements were performed in a climate-controlled room with continuous measurement of the temperature (20 ± 1°C) and relative humidity (40 ± 2%). To ensure comparable and accurate weighing conditions, all air filters were acclimatized for at least 5 days in the climate-controlled room before weighing. Static charge was eliminated prior to weighing the filter at all occasions using a ^{210}Po Staticmaster® (NRD LLC, NY, USA).

Field blanks consisted of sampling cassettes loaded with filters, which were taken to the field together with the sample cassettes but were never opened (i.e. kept sealed). One field blank for every 10 particulate samples, with at least 1 blank per day, was included. All blanks were analysed gravimetrically for thoracic dust and were below the LOD.

Chemical analysis

All reagents and water used for chemical analysis were of analytical quality.

The impregnated filter pads were placed in polypropylene tubes (Prod. No. 62.554.001, Sarstedt AG & Co, Germany) and leached in deionized water. Bromide was added as internal standard to all sample solutions. The concentrations of nitrite (NO_2^-) and nitrate (NO_3^-) were determined by ion chromatography using a Dionex DX-500 ion chromatograph (Dionex, Sunnyvale, CA, USA) (Hovland *et al.*, 2012). The LOD for NO_2 was 20 µg (21 µg m^{-3} based on an 8-h sampling period at a flow rate of 1.6 l min^{-1}).

Oil mist was determined using a model Spectrum 100 Fourier transform infrared spectrophotometer (Perkin Elmer, Waltham, MA, USA), and oil vapour was determined using a Perkin Elmer Autosystem XL gas chromatograph and a flame ionization detector (Galea *et al.*, 2012). The LOD for oil mist and oil vapour was 0.05 and 0.1 mg m^{-3}, respectively, based on a 2-h sampling period at a flow rate of 1.4 l min^{-1}.

EC and OC were determined by Sunset Laboratory Inc. (Tigard, OR, USA) using an OCEC Dual-Optical Analyzer according to NIOSH Method 5040 (NIOSH, 2003). The LOD of the method is ~2 ng m^{-3} and 2 µg m^{-3} based on an 8-h sampling period at a flow rate of 2.0 l min^{-1} collected on a 37-mm filter with a 1.5 cm^2 punch from the sample filter for EC and OC, respectively. The accuracy of this method for measuring total carbon was ascertained in this measurement campaign by analysing a known quantity of carbon in the form of sucrose.

The α-quartz content in the thoracic mass sub-fraction was measured by X-ray diffraction spectrometry, applying Philips PW1729 X-ray generator, Philips 1710 diffractometer control, Philips PW2253/20 X-ray tube, and Philips PW1050 goniometer. α-Quartz content was determined according to NIOSH Method 7500 (NIOSH, 2003). The LOD (3 × standard deviation of field blank filters) was 10 µg (13.0 µg m^{-3} based on an 8-h sampling period at a flow rate of 1.6 l min^{-1}).

Data analysis

The frequency distribution was examined visually using probability plots and indicated that a log-normal distribution provided a better fit to the exposure data. The data were therefore ln-transformed before statistical analysis. The measured air concentrations were used without further adjustments. Air concentrations were summarized by geometric means (GM), GSD, minimum concentrations (Min), and maximum concentrations (Max) using maximum likelihood estimation (MLE). AM was estimated from the expression $\mathrm{EXP}[\ln\mathrm{GM} + 0.5\ \ln\mathrm{GSD}^2]$ (Seixas *et al.*, 1988). The SAS procedure NLMIXED was used to perform MLE for repeated measures data subject to left censoring and for calculation of WW and BW variance components for all contaminants except for NH_3 where the SAS procedure LIFEREG was used because there was no repeated measurements (Jin *et al.*, 2011). To perform MLE computations, the SAS program uses numerical values above the LOD, information on the proportion of data below the LOD, and a mathematical formula for an assumed distribution of the data.

To evaluate the significance of fixed effects on the BW and WW variance components, values of the variance components obtained from the mixed-effect models were compared to values obtained from the random-effects model without fixed effects. The percentage of the total variance explained by the fixed effect (job group) was calculated by subtracting the sum of the WW and BW variances from the total variance (random effects only).

The likelihood ratio test was used to compare the models with random effects to those having both random- and fixed effects.

Correlations between exposure variables were evaluated using Spearman's correlation coefficient.

Statistical analyses were carried out with SPSS 21.0 (SPSS Inc, Chicago, IL, USA) and SAS version 8.2 (SAS Institute Inc., Cary, NC, USA).

RESULTS

A total of 90 tunnel construction workers carried personal sampling equipment in the exposure study, and all workers were monitored twice. Few workers reported use of personal protective respirators, except shotcreting operators who used filtering half mask respirators with P3 filters for filtering solid and liquid particles (3M™) part of the sampling time. In total, 6 samples of α-quartz and 20 samples of EC and OC were discarded because of technical failures.

In total, 79 personal full-shift samples of NO2 using direct-reading instruments (DRI) were evaluated. Only 8 of these measurements had time-weighted average (TWA) above the LOD of 376 μg m^{-3} (results not shown). The median NO2 TWA concentration of samples above LOD was 565 μg m^{-3} (range: 376–1317 μg m^{-3}) (results not shown). However, in 17 of the DRI measurements, maximum observed peak value incidents for a 30-s averaging period of NO$_2$ were detected (>3764 μg m^{-3}).

Table 2 gives an overview of air concentrations by contaminant. The GM air concentrations for the thoracic mass aerosol sub-fraction, α-quartz, oil mist, OC, EC, NO$_2$ (filter), and NH$_3$ for all workers were 561, 63, 210, 146, 35.2, 120, and 251 μg m^{-3}, respectively (Table 2). Statistical differences of air concentrations between job groups were observed for all contaminants, except for OC, EC, and NH$_3$ ($P > 0.05$). On average, OC accounted for 76% of the total carbon measured, and total carbon accounted for 49% of the thoracic aerosol mass (results not shown). Also, statistical differences of air concentrations of α-quartz between construction sites were observed ($P < 0.05$). The AM percent of α-quartz in the thoracic mass aerosol sub-fraction ranged from 3 to 40% between sites (results not shown).

Tables 3 and 4 give an overview of air concentrations by job group. The shaft drillers, injection workers, and shotcreting operators were exposed to the

Table 2. Air concentrations (μg m^{-3}) during tunnel construction work by contaminant

Contaminant	*N*[a]	*N* < LOD[b]	*K*[c]	AM[d]	Percentiles		GM[e]	GSD[f]	Likelihood ratio test[g]
					10	90			*P* value
Thoracic mass fraction	163	0	89	756	230	1300	561	2.0	<0.0001
α-Quartz in thoracic mass fraction	162	11	85	127	15.7	267	63.0	3.3	<0.01
Organic carbon	149	0	89	170	77.0	318	146	1.7	0.33
Elemental carbon	149	0	89	55.5	8.95	97.7	35.2	2.6	0.07
Nitrogen dioxide, filter	163	0	85	170	0.05	0.4	120	2.2	<0.001
Oil mist	56	12	38	960	<50.0	2000	210	5.7	<0.0001
Ammonia	56	22	56	1533	<1394	6900	251[h]	6.8	0.63

Seventy-nine samples of direct-reading measurements of nitrogen dioxide were collected, of these 8 samples were above the LOD (376 μg m^{-3}); range: 414–1261 μg m^{-3}. Fifty-six samples of oil vapour were collected. All individual measurements of oil vapour were below 620 μg m^{-3} (LOD = 100 μg m^{-1}).

[a] Number of measurements.

[b] Number of measurements below the LOD.

[c] Number of persons.

[d] AM, estimated from EXP[lnGM + 1/2 lnGSD^2].

[e] GM, estimated using MLE by the NLMIXED procedure in SAS, except for ammonia where the LIFEREG procedure was used.

[f] GSD, estimated using MLE by the NLMIXED procedure in SAS, except for ammonia where the LIFEREG procedure was used.

[g] The likelihood ratio test was used to compare the models with random effects to those having both random- and fixed effects (job group).

[h] Although individual measurements exceeded the LOD, the average GM is below LOD due to the large number of LOD measurements.

Table 3. Air concentrations (μg m^{-3}) of thoracic mass, α-quartz, organic- and elemental carbon, and nitrogen dioxide in tunnel construction work stratified by job group

Job group	*N*[a]	Thoracic mass		α-Quartz[b]			Organic carbon		Elemental carbon		Nitrogen dioxide	
		GM[c]	GSD[d]	*N* < LOD[e]	GM	GSD	GM	GSD	GM	GSD	GM	GSD
Drill and blast workers	52	501	1.9	3	61.4[f]	3.1	147[f]	1.8	29.9[f]	2.6	104	2.1
Drill and blast mechanics	34	423	1.9	6	43.1	4.1	178[g]	2.0	31.8[g]	2.5	111	2.0
Support workers	34	603	1.8	0	118	2.4	138[h]	1.6	55.8[h]	2.2	159	2.2
Loaders	20	456	1.5	2	39.2	2.7	152[i]	1.7	21.8[i]	2.9	120	2.2
Injection workers	13	1087	1.5	0	42.9	2.0	104	1.3	47.5	2.2	77	1.4
Shotcreting operators	8	865	1.3	0	78.7	3.0	121[j]	1.3	48.3[j]	1.8	133	1.8
Shaft drillers	2	7061	1.6	0	844	2.0	NA[k]		NA[k]		1919	1.0

[a] Number of measurements.
[b] α-Quartz in the thoracic mass fraction.
[c] GM, estimated using MLE by the NLMIXED procedure in SAS.
[d] GSD, estimated using MLE by the NLMIXED procedure in SAS.
[e] Number of measurements below the LOD.
[f] $N = 51$.
[g] $N = 29$.
[h] $N = 31$.
[i] $N = 18$.
[j] $N = 7$.
[k] $N = 0$.

highest air concentrations of thoracic aerosol mass (GM = 7061, 1087, and 865 μg m^{-3}, respectively). The shaft drillers and the support workers were exposed to the highest concentrations of α-quartz (GM = 844 and 118 μg m^{-3}, respectively). Shotcreting operators and drill and blast workers were the highest exposed workers to NH_3 (GM = 2927 and 2857 μg m^{-3}, respectively). The highest levels of NH_3 were found during loading of crushed rock into dump trucks using an excavator following detonation of the explosive. An example is shown in Fig. 1.

In models with only random effects, the BW component was higher than the WW component for all contaminants (Table 5). When job group was added as fixed effect, the BW variance components were reduced for all contaminants (13–59%). Job group explained between 7 and 57% of the total variance (Table 5).

Table 6 shows the correlation matrix between exposure variables. No correlation coefficient exceeded 0.6. The highest correlations were between air concentrations of OC and oil mist and between EC and NO_2 [$r_{\text{Spearman}} = 0.56$ and 0.60, respectively ($P < 0.0001$)].

DISCUSSION

As part of a 11-day follow-up study on the relationship between personal exposure to aerosols and gases and possible cardiovascular and respiratory effects in Norwegian tunnel construction workers, an exposure survey was performed in 2010 and 2011. Tunnel construction workers are a mobile workforce, who perform a number of tasks and are in contact with many different materials at different worksites. These characteristics challenge the exposure assessment process, and measurements performed at a single worksite may not be valid at other sites or time periods. In this study, we measured air concentrations of selected contaminants at 11 different worksites. Overall, the results indicate that the air concentrations have slightly decreased for some contaminants and have been reduced for some jobs compared with measurements

Table 4. Air concentrations (μg m^{-3}) of oil mist and ammonia in tunnel construction work stratified by job group

Job group	Oil mist				Ammonia			
	N[a]	*N* < LOD[b]	GM[c]	GSD[d]	*N*	*N* < LOD	GM	GSD
Drill and blast workers	17	4	130	3.7	19	7	2857	28
Drill and blast mechanics	15	0	420	2.7	11	4	355[e]	34
Support workers	4	2	<50.0	5.8	9	3	376[e]	22
Loaders	11	1	240	3.1	9	2	1533	17
Injection workers	5	5	<50.0		7	6	<0.0001[e]	1355
Shotcreting operators	0		NA		1	0	2927	1.0
Shaft drillers	4	0	9100	1.6	0	0	NA	

NA = not applicable.

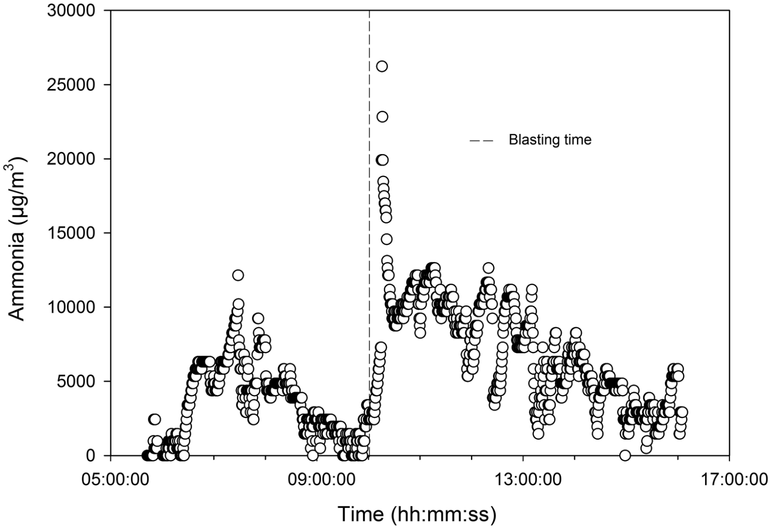
[a] Number of measurements.

[b] Number of measurements below the LOD.

[c] GM, estimated using MLE by the NLMIXED procedure in SAS, except for ammonia where the LIFEREG procedure was used.

[d] GSD, estimated using MLE by the NLMIXED procedure in SAS, except for ammonia where the LIFEREG procedure was used.

[e] Although individual measurements exceeded the LOD, the average GM is below LOD due to the large number of LOD measurements.



1 Personal ammonia concentrations (μg m^{-3}) measured for one person in the job group loader who loads crushed rock into dump trucks.

in this industry 10–15 years ago (Bakke *et al.*, 2001a). However, challenges remain especially with regard to airborne dust concentrations.

The health outcomes studied in this investigation were lung function and cardiovascular risk factors such as systemic inflammation and coagulation. The thoracic aerosol mass fraction was measured in order to assess the mass penetrating beyond the larynx into the bronchi where the health effects of this study are expected. If we had studied specifically health effects originating in the alveoli, which is relevant for α-quartz, the respirable fraction should have been chosen. Currently there is no recommended occupational exposure limits (OEL) for 'nuisance' dust expressed in

Table 5. BW and WW variance components for air samples

Contaminant	*N*[a]	*K*[b]	Random effect model		Mixed effects model				
			Variance[c]		Variance		% variance explained by fixed effects		
			BW	WW	BW	WW	BW	WW	Total
Thoracic dust	163	89	0.26	0.23	0.12	0.23	54	0	29
α-Quartz (in thoracic dust fraction)	162	85	0.94	0.47	0.70	0.47	26	0	16
Organic carbon	149	84	0.16	0.15	0.14	0.15	13	0	6.6
Elemental carbon	149	84	0.48	0.43	0.39	0.43	19	0	10
Nitrogen dioxide	163	85	0.36	0.28	0.23	0.28	36	0	20
Oil mist	56	51	2.9	0.13	1.2	0.093	59	28	57

[a]Number of measurements.
[b]Number of persons.
[c]Variance components estimated using MLE by the NLMIXED procedure in SAS.

Table 6. Correlation matrix of exposure variables (Spearman's correlation coefficient)

		Thoracic mass fraction	α-Quartz	Organic carbon	Elemental carbon	Oil mist	Nitrogen dioxide
Thoracic mass fraction	*r*	1.0	0.42[a]	0.20[b]	0.51[a]	−0.17	0.30[a]
	N[c]	163	162	148	148	51	163
α-Quartz	*r*		1.0	0.01	0.33[a]	0.15	0.20[b]
	N		162	147	147	51	162
Organic carbon	*r*			1.0	0.22[a]	0.56[a]	0.35[a]
	N			149	149	44	148
Elemental carbon	*r*				1.0	−0.12	0.60[a]
	N				149	44	148
Oil mist	*r*					1.0	0.41[a]
	N					56	51
Nitrogen dioxide	*r*						1.0
	N						163

[a]Correlation is significant at the 0.01 level.
[b]Correlation is significant at the 0.05 level.
[c]Number of measurements.

terms of the thoracic mass concentration in Norway and elsewhere.

Particles are generated by drilling, blasting, crushing, grinding, shotcreting, and transport operations. The mass of particles in the thoracic aerosol sub-fraction was substantial during shaft drilling (GM = 7.1 mg m^{-3}). During work, the shaft drillers are restricted to the confined space defined by the raise climber.

Ventilation is not mechanically installed because the space is not large enough. Instead, ventilation is provided by supply of compressed air through pipes in the guide rail. Among other jobs, the GM thoracic air concentration varied between 0.42 and 1.1 mg m^{-3} (drill and blast and injection workers, respectively). In former studies of shaft drillers and drill and blast workers, we found that the GM of 'total' dust was 6.1 and 2.3 mg m^{-3}, respectively, and the GM of respirable aerosol sub-fraction was 2.8 and 0.91 mg m^{-3}, respectively (Bakke *et al.*, 2001a). When compared with the former studies, the air concentrations during shaft drilling seem to remain high, whereas the exposure levels among drill and blast workers seem to have decreased. One plausible explanation for this decrease in air concentrations could be improvements in the mechanical ventilation system and machinery.

Any process that involves movement of earth may potentially expose workers to α-quartz because α-quartz is a naturally occurring substance in the earth. The main work task, in which exposure to α-quartz occurs in tunnel construction, is rock drilling. In addition, inhalation of the aerosol generated during blasting may also increase α-quartz exposure. The air concentration of α-quartz during shaft drilling was very high (GM = 0.84 mg m^{-3}) compared with Norwegian 8-h TWA OEL of 'total' dust and respirable dust (0.3 and 0.1 mg m^{-3}, respectively) (NLIA, 2013). These levels are also higher than (Sauve *et al.*, 2013) found in a study where they modelled the impact of tasks performed on silica exposure and identified drilling as a high silica-exposed task in tunnel construction (GM = 0.27 mg m^{-3} respirable silica). The support workers who work about 100 m from the tunnel face also experienced high air concentrations of α-quartz compared with these standards (GM = 0.12 mg m^{-3}). Statistical significant differences in air concentrations of α-quartz between construction sites were observed, probably due to differences in geology. The high air concentrations reported in this study are therefore most likely as a result of high α-quartz content in the ground and that large amount of aerosol is generated during rock drilling. Underground project planning requires detailed geological documentation. Information in these reports could be used in risk assessment of geological hazards, such as α-quartz. α-Quartz may cause serious pulmonary diseases (Hnizdo and Vallyathan, 2003; Tjoe Nij and Heederik, 2005). Studies have also shown that inhalation of freshly fractured quartz, such as during drilling and blasting, may lead to enhanced lung injury compared with inhalation of aged quartz (Vallyathan *et al.*, 1995).

The solid particle fraction of diesel exhaust is predominately composed of EC. EC has been proposed to be the most reliable marker of this particle phase of diesel exhaust (NIOSH, 2003). Few countries have regulated occupational exposure to diesel exhaust particulate matter, measured as EC. In Austria, the 8-h TWA OEL is 100 µg m^{-3} (Austria Arbeitsinspektion, 2013). In our study, the overall GM air concentration of EC varied from 31 to 54 µg m^{-3} for all job groups. This is considerably lower than what was previously reported where we found an overall GM of 160 and 340 µg m^{-3} among drill and blast workers (Bakke *et al.*, 2001a). This indicates that workers in these jobs are being considerably less exposed to diesel exhaust. One plausible explanation for the reduction in exposure over this time period is that the industry may have responded to an increasing awareness of the potential detrimental health effects of diesel particle exposure, by for instance installing more particle removing filters in the vehicles. Other studies in Sweden and Switzerland among tunnel construction workers have reported EC levels of 80–90 µg m^{-3} (Sauvain *et al.*, 2003; Lewné *et al.*, 2007).

Particulate emission rates of EC and OC from diesel engines may vary greatly depending on the mode of vehicle operation. Typically EC/OC ratios under normal operating conditions are ~2.5 (Shah *et al.*, 2004). In our study, OC constituted on average 76% of the total carbon, and the main source is therefore probably not diesel exhaust. The air concentrations of OC were moderately correlated to the air concentrations of oil mist ($r_{\text{Spearman}} = 0.56$), and OC may therefore partly be an expression of exposure to oil mist in tunnelling. Sampling of oil mist and oil vapour was restricted to only a 2-h sampling period with a flow rate of 1.4 l min^{-1} to prevent evaporation of oil mist from the filter. Also, the oil mist measurements were targeted to measure air concentrations of expected high exposed work tasks (e.g. rock drilling) to capture exposure from lubricating oil. This may explain why the measured air concentration of oil mist is higher than the air concentration of OC. Alternatively, because the sampling duration of EC/OC was 8 h with a flow rate of 2 l min^{-1}, it is also possible that OC to some extent may have evaporated from the filter.

Machines used for drilling of shafts and tunnels require that the cutting head is lubricated. Oil mist and oil vapour may therefore be released into the work atmosphere. The GM air concentration of oil mist varied between <50 and 9100 µg m^{-3}. The highest GM air concentrations of oil mist were measured during shaft drilling using pneumatic drilling equipment (9100 µg m^{-3}). These levels are in excess of the Norwegian OEL of 1000 µg m^{-3} (NLIA, 2013). The results in this study indicate that the air concentrations of oil mist have been reduced, except among shaft drilling workers where the levels seems to have increased compared with a previous study (GM = 1400 µg m^{-3}) (Bakke *et al.*, 2001a). The air concentrations that were measured during shaft drilling are known to affect lung function and should be prevented (Skyberg *et al.*, 1992; Svendsen and Hilt, 1999). All individual measurements of oil vapour was low (<0.62 mg m^{-3}) representing <2% of the Norwegian OEL 50 mg m^{-3}, also indicating that the oils in use were of low volatility.

The main sources of NO_2 during tunnel construction are blasting and exhaust from diesel-powered machinery and vehicles. The amount of gases released during blasting depends on the type of explosive used (Bakke *et al.*, 2001b). In this study, emulsion explosive was the explosive of choice in all construction sites, and this may explain the relative low levels of NO_2 (GM = 120 µg m^{-3}), which was similar to findings in former studies where the same emulsion explosive was used (GM = 226 µg m^{-3}) (Bakke *et al.*, 2001b). These levels represent <20% of the Norwegian OEL of 1100 µg m^{-3} (NLIA, 2013) and was considerably lower than what was reported in an Italian study (AM = 1100–3200 µg m^{-3}) (Arcangeli *et al.*, 2004). Different analytical methods have been used to measure NO_2 in these studies, and as shown in this study DRI do not have the sensitivity that is required for measuring full-shift NO_2 air concentrations during tunnel construction.

Overall, the BW variability was larger than the WW variability for all measured contaminants. When the workers were divided into job groups based on performance of similar tasks, the BW variance was considerably reduced. Optimal grouping of workers should also be based on other determinants, e.g. tasks performed, which may influence the WW variance component and provide additional information on how to reduce exposures among the workers. The sampling strategy was not targeted to capture information on these other determinants of exposure and therefore could not be evaluated in this study.

There is a possibility that the measurements, which were collected on 2 consecutive days, may not be independent. This can result in biased estimates of the mean and variance of the exposure distribution. To account for auto correlation, a first-order autoregressive covariance structure ideally should have been used instead of compound symmetry. However, because the measurements were collected in two time points, the choice of covariance structure will not influence the results.

Use of respirators was not mandatory and was not used on a general basis, except among shotcreting operators who used half mask respirators with particle filters part of the sampling time. The actual inhaled air concentrations of particles may therefore be lower than measured among workers in this job. Consideration must also be given to whether these masks are appropriate for protecting the workers given the fact that they do not protect against agents such as inorganic gases and volatile organic compounds.

In conclusion, findings from this study show significant differences between job groups with shaft drilling as the highest exposed job to air concentrations for all measured contaminants. Technical interventions in this job should be implemented to reduce exposure levels. Overall, diesel exhaust air concentrations seem to be lower than previously assessed (as EC).

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