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Exposure to Metalworking Fluid Aerosols and Determinants of Exposure

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Metalworking fluid (MWF) aerosols are associated with respiratory disorders including asthma and hypersensitivity pneumonitis. The aims of this study were to describe exposure to inhalable MWF aerosols and volatile compounds in machine shops, to estimate the influence of important determinants of exposure and to compare different sampling techniques for MWF aerosols. Personal full-shift air samples of inhalable aerosol (PAS-6 sampler) and total aerosol (open-faced sampler) were collected on operators in five medium to big-sized machine shops in three companies. The filters were analysed gravimetrically and extracted by supercritical fluid extraction for MWF aerosol and triethanolamine content. In addition, personal measurements were taken for formaldehyde and volatile compounds on adsorbent samplers. Continuous dust measurements were performed with a real-time instrument (DataRAM) during 2 h periods, using 1-min average values. In total, 95 measurements of inhalable aerosol and extracted MWF aerosols on 51 operators were conducted. Within the companies, the average exposure to inhalable aerosol ranged from 0.19 to 0.25 mg m^{-3} with geometric standard deviations from 1.56 to 1.79. On average, the extracted fraction of MWF aerosol was 67% of the inhalable aerosol concentration. The exposure levels of triethanolamine, formaldehyde and volatile compounds were generally low. About 45% of the between-worker variance could be explained by use of compressed air, lack of complete enclosure of machines or grinding as cutting task. In 21 workers with continuous aerosol measurements, short-term peak exposures during 6% of the work time contributed to ~25% of the average concentration of inhalable MWF aerosol. Inhalable MWF aerosol concentration measured with the PAS-6 sampler was a factor 2 higher than the concentrations derived from the open-faced sampler. These findings suggest that control measures, such as full enclosure of machines and the elimination of the use of compressed air as cleaning technique, are required to reduce the exposure to MWF aerosols to levels below the expected threshold for adverse respiratory health effects.

Keywords: determinants of exposure; inhalable aerosol exposure; machine operators; metalworking fluid aerosols; real-time instrument

INTRODUCTION

Metalworking fluids (MWFs) are used for lubricating, cooling and/or to minimize corrosion in metalworking processes. These fluids comprised complex mixtures and can be divided into four major categories: straight oils (mineral and/or fatty oils, insoluble in water), soluble MWFs (water emulsion with high oil contents), semi-synthetic MWFs (water emulsion with lower oil contents) and synthetic MWFs (chemical solutions of organic compounds and inorganic salts in water without any oils) (OSHA, 1999). During machining processes, aerosols from the MWFs are generated together with thermal degradation products from the machining process, fine metallic particles as well as microbial fungi and bacteria from water fluids. Machine operators are exposed to MWF aerosols by inhalation and direct skin contact.

Exposure to MWF aerosols is associated with respiratory disorders and dermatitis (NIOSH, 1998; OSHA, 1999). Greaves *et al.* (1997) found that operators exposed to MWFs had a higher prevalence of cough, phlegm, wheezing and breathlessness than assembly workers not exposed to MWFs. In an investigation of Oudyk *et al.* (2003), operators exposed to

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MWF aerosols in the range of 0.25–0.84 mg m^{-3} had significantly more wheezing, chest tightness, sore and hoarse throat as well as upper respiratory symptoms compared with low-exposed workers (0.02–0.09 mg m^{-3}), and exposure–response associations seemed stronger for workers with regular peak exposure. Changes in airway responsiveness were shown to be higher in apprentices exposed to water-based MWFs, especially synthetic MWFs, compared to apprentices without exposure (Kennedy *et al.*, 1999). There is some evidence that health effects may differ across different MWFs. Eisen *et al.* (2001) found that exposure to straight oil aerosols was associated with a decrease in lung spirometry [forced expiratory volume (FEV_1)], whereas this was not observed for exposure to water-based MWFs.

Several studies have reported on exposure patterns of MWF aerosols in industry. However, the comparison among studies is hampered due to lack of insight into determinants of exposure and due to different measurement techniques (Woskie *et al.*, 2003). Ross *et al.* (2004) reported that type of machine, task performed and shop characteristics were associated with the magnitude of MWF exposure, but comparable analyses have not been presented. Different measurement techniques have been used. In North American countries, total dust closed-faced cassette for 'total' MWF aerosol (NIOSH, 1998; Glaser *et al.*, 2003) and PM_{10} cyclones for the thoracic fraction (Piacitelli *et al.*, 2001; NIOSH, 2003; Ross *et al.*, 2004; Verma *et al.*, 2006) are recommended methods, whereas in the UK, assessment focuses on seven-hole inhalable sampler (Simpson *et al.*, 2003). Kriebel *et al.* (1997) have used the seven-hole inhalable sampler in an American investigation. Comparative measurements in machine shops using straight oils showed that the total dust closed-faced sampling technique considerably undersamples with respect to inhalable aerosol measured with the Institute of Occupational Health (IOM) sampler for inhalable dust (Wilsey *et al.*, 1996). Another approach is to extract the MWF fraction from the collected aerosol in order to distinguish between MWF aerosol and background dust and particulate metallic materials (Glaser *et al.*, 2003; NIOSH, 2003), but information on the extracted fraction across different MWFs work processes is lacking. In the UK, MWF aerosols from straight oils are extracted with cyclohexane (HSE, 1997), while for water-mix MWF aerosols an elemental marker method is used (HSE, 2003). Thus, there is a clear need for surveys comparing different measurement techniques and approaches in order to facilitate comparability among studies.

The aims of this study were to describe exposure to inhalable MWF aerosols and volatile compounds in machine shops, to estimate the influence of important determinants of exposure and to compare different sampling techniques for MWF aerosols.

MATERIALS AND METHODS

Workplaces

Three large companies in different regions in Sweden were contacted and willing to participate in the study. These companies produced different products in alloyed steel, cast iron and aluminium. One company had three different machine shops, producing bearings of different sizes. Types of MWFs and additives differed across these facilities. Exposure measurements took place from May 2005 to November 2006.

Exposure measurements

Personal full-shift air samples (6–8 h) were collected on operators handling the machines within the five machine shops. Each operator was sampled twice. The main sampler was the Dutch PAS-6 sampler for inhalable aerosols with 25 mm polytetrafluoroethylene filters with 3-μm pore size (PTFE from Gelman Sciences, Ann Arbor, MI, USA) (Kenny *et al.*, 1997). The airflow was 2 l min^{-1} and sampling pumps used were SKC, GilAir and Gilian. A number of workers were selected for parallel sampling, wearing both the PAS-6 sampler and a total aerosol open-faced sampler (25 mm PTFE filter, airflow 2 l min^{-1}).

At all machine shops, two to six machine operators also wore a real-time instrument (DataRAM) during 2 h. Some of the operators also had samplers for volatile compounds (Anasorb 747, GilAir pumps and airflow of 50 ml min^{-1}) and/or samplers for aldehydes (active sampling Sep-Pak, passive sampling Umex). The samplers were attached close to the machinist's collar in the breathing zone.

Analysis

Filters Before and after sampling, the filters were conditioned in a climate chamber (25 ± 1.0°C, relative humidity 50 ± 5.0) for at least 24 h before weighing with a microbalance with a sensitivity of ±1 μg and a limit of detection of 10 μg. The filters for inhalable aerosol (PAS-6 sampler) were also extracted by supercritical fluid extraction (SFE) in order to measure the amount of MWF aerosols in the inhalable dust. The SFE method has been shown to extract 90–98% of different classes of MWFs spiked on filters (Brudin *et al.*, 2006). The extracts were analysed for the triethanolamine content with gas chromatography with nitrogen/phosphor detector.

Formaldehyde and volatile agents. The volatile compounds sampled on activated carbon were analysed by gas chromatography-flame ionization detector and the samplers for formaldehyde with high-performance liquid chromatography with ultraviolet detection.

DataRAM. DataRAM (MIE pDR1000) is a real-time instrument based on passive sampling using nephelometric monitoring. The instrument is logging the results every 10 s, but in the current study 1-min average values were used. The DataRAM measures predominately particles between 0.1 and 10 μm. The measurement range is 1 μm m^{-3} to 400 mg m^{-3}. Before each sampling day, the DataRAM was set to zero with particle-free air.

Determinants of exposure

Information on potential determinants of exposure was obtained from three sources: the operators, the occupational hygienists responsible for the sampling and the managing staff. The operators sampled filled in a questionnaire at the end of the shift about the machines used, metal machined, MWFs used, use of compressed air and machining operations during an average shift. The occupational hygienist, together with management, evaluated the machine enclosure, number of other machines operating in the shop, ventilation and other shop characteristics. During the measurements with the DataRAM, operators were asked to fill in their current working task and use of pressured air every 15 min. No welding or other dust-generating activities were observed during the measurements.

Table 1 describes the potential factors of influence for the exposure pattern of MWFs, distinguishing the companies ($n = 3$), machine shops ($n = 5$), machining tasks (primarily grinding versus others), type of operation (single or multiple machines), the use of compressed air and the level of enclosure of the machines.

Data analysis

Descriptive statistics were used to calculate means (arithmetic and geometric) and geometric standard deviations (GSDs) of the MWF exposure. The inhalable and extractable MWF concentrations were lognormally transformed before fitting a linear mixed-effect model for repeated measurements. In the mixed-effect model, the potential determinants of exposure were included as fixed (categorical) effects since these determinants were collected at the level of the individual worker. The variances between and within workers were regarded as random effects. The random variance component was pooled across all determinants of exposure and assumed to be equal across all fixed determinants. This assumption of a compound symmetry covariance structure, resulting in the most restrictive error structure possible, was chosen because of the relatively few measurements available in some determinants, which limited the number of parameters that could be estimated in the model (Burdorf, 2005). For most mixed-effect models, this assumption on error structure was not violated against tests of significance for change in the goodness-of-fit. Given the observation that the potential determinants of exposure were interrelated, the first step in the analysis was a separate mixed-effect model for each determinant as fixed effect. The determinant that had the largest reduction in the between-worker variance was retained in the second step. In this step, other determinants were stepwise introduced into the mixed-effect model and evaluated for their improvement in the explained variance. Akaike information criterion (AIC) was used as measure of the overall fit of the model and additional determinants were retained in the mixed-effect model when resulting in a significant improvement in the overall fit. The AIC was used instead of the more conventional −2 log likelihood measure since the AIC attempts to find a model that best explains the data with a minimum of parameters.

A similar mixed-effect model analysis was performed on the continuous measurements of inhalable aerosol on 21 workers with the DataRAM. In order to evaluate the influence of short-term peaks on the overall concentration per worker, a short-term peak was defined as an exposure level in a 1-min sample of at least twice the average exposure over the complete duration of sampling per worker. A linear regression analysis was performed to estimate the influence of percentage of work time with peak exposure on the average concentration per worker. In all linear regression models, the regression coefficient represents the change in the dependent variable (MWF concentration) due to a one unit change in the explanatory variable (exposure determinant).

All analyses were conducted using the procedure Proc Mixed in SAS version 6.12 software (SAS Institute, Cary, NC, USA).

Table 1. Potential factors of influence for the exposure pattern of MWFs

Exposure determinant	Description
Company	Three different companies, one company with three machine shops
Type of machining tasks	Primarily turning, deburring, milling, drilling
	Primarily grinding
Type of operation	Single-operating machine
	Multiple operating machine
Compressed air	Use of compressed air for cleaning minute per shift, categorized into no use, 1–30 min day^{-1} and >30 min day^{-1}
Enclosure of machines	Enclosed or almost enclosed (partly) open (five sides or less)

RESULTS

Machine shops

In the three factories, five machine shops were studied (Table 2). Most machines were highly automated and (almost) fully enclosed. In most shops, more than one type of MWF was used during the production of metal pieces, varying from small to medium pieces of about 0.2–10 kg except in machine Shop 3 with bearings up to 1 ton with machining times from a few minutes to several hours. In all shops, general ventilation and exhaust ventilation systems were present. The general ventilation varied from 2.5 to 5.2 turnovers h^{-1}. Most of the operators worked in the direct vicinity of the machines during the whole shift. When not machining, the operators programmed the machine, performed quality measurements, changed tools or products, used compressed air for cleaning and conducted repairs. A limited time was spent away from the machines, e.g. transporting product and doing administrative tasks. During most shifts, operators performed the same routine activities on the same machines.

Full-shift exposure levels

In total, 95 measurements of inhalable and extracted MWF aerosols on 51 operators were conducted in three companies. All measurements were above the limit of detection. The average exposure to inhalable aerosol ranged from 0.19 to 0.25 mg m^{-3} with GSDs from 1.56 to 1.79 (Table 3). On average, the extracted fraction of MWF aerosol was 67% of the inhalable aerosol concentration. In all companies, the between-worker variance, for inhalable and extracted aerosols, was much larger than the within-worker variance, with variance ratios from 0.10 to 0.30. The exposure levels of triethanolamine, formaldehyde and volatile compounds were generally low. Triethanolamine was an MWF additive used only in the machine shops in Company 2. The highest amount of volatile compounds was found in Company 2, where polishing oils were frequently used.

Table 4 presents the results of the mixed-effect model, demonstrating that the prolonged use of compressed air, working with partly open machines and grinding as cutting task were important determinants of exposure to inhalable aerosol. Company, machine shop and type of MWF were not associated with inhalable aerosol exposure. However, type of operation, use of compressed air and grinding as cutting task were statistically significantly interrelated. In addition, since cutting task and machine enclosure were also highly associated, two separate models are presented with comparable overall goodness of fit. In both models, the determinants of exposure explained 28 and 23%, respectively, of the

Table 2. Characteristics of companies and machine shops using MWF in Sweden

Companies	Machine shop	Metals machined	No. of machines	Shop area m^2 (height m) (turnovers h^{-1})	Operators per shift	Workers measured	Type of MWF	Machining operation (size of products in kg)	Age of machine shop
1	1	Alloyed steel, aluminium	40	7000 (6–8) (2.5)	20	9	One straight, two soluble	Turn, drill, mill, deburr, grind (0.5–10)	1998
2	2	Alloyed steel, cast iron	17	3000 (4.5) (2.5 and 5.2)[†]	17	13	Two synthetic	Turn, grind, polish, deburr (2–1000)	1980
2	3	Alloyed steel	50	15 000 (8) (2.5–3)	15	9	One semi-synthetic	Grind, turn, polish, honing (0.2–5)	1970
2	4	Alloyed steel	80	15 000 (8) (5)	20	7	One soluble, one semi-synthetic	Grind, polish (0.5–1.5)	1970
3	5	Alloyed steel, cast iron	30	12 000 (8) (2.5)	20	14	Three straight, one soluble and one synthetic	Drill, mill, turn, deburr, grind, polish (0.5–5.5)	1995

[†] The machine shop has two production units of 1600 and 1500 m^2 with different ventilation.

Table 3. Personal measurements of inhalable aerosol and extracted MWF aerosols, TEA, formaldehyde and volatile components in companies in Sweden

Company	*N*	*n*	AM	GM	GSD	Range	wW (%)	bW (%)
Inhalable aerosol								
1	9	17	0.23	0.20	1.79	0.04–0.53	23	77
2	28	52	0.25	0.21	1.77	0.08–1.30	10	90
3	14	26	0.19	0.17	1.56	0.08–0.57	11	89
Extracted fraction MWF aerosol								
1	9	17	0.14	0.12	1.71	0.03–0.39	22	78
2	28	52	0.17	0.14	1.80	0.06–1.03	10	90
3	14	26	0.14	0.12	1.80	0.04–0.49	9	91
TEA in extracted fraction								
1		0						
2	18	34	0.014	0.010	2.50	0.001–0.063	20	80
3		0						
Formaldehyde								
1	2	4	0.128	0.125	1.29	0.087–0.154	69	31
2	19	33	0.012	0.009	2.24	0.002–0.042	13	87
3	11	16	0.003	0.003	1.57	0.001–0.007	14	86
Volatile compounds								
1		0						
2	20	36	6.25	3.11	3.53	0.51–29.4	3	97
3	4	8	1.79	0.87	3.67	0.20–5.30	90	10

N, number of workers; *n*, number of measurements; AM, arithmetic mean; GM, geometric mean; wW, within-worker variance; bW, between-worker variance; TEA, triethanolamine.

Table 4. Determinants of exposure to inhalable aerosol, estimated by mixed-effect models for 95 (I) and 93 (II) repeated measurements (two samples from one very high exposed worker excluded).

Determinant	*n*	Model fit (AIC)	Regression coefficient	wW	bW
Intercept only	95	125.4	−1.63	0.078	0.214
I					
Intercept		115.8	−1.84	0.081	0.155
Compressed air > 30 min per shift**	11		0.61 ± 0.19		
Partly open machines**	34		0.38 ± 0.13		
Intercept	11	118.2	−1.55	0.081	0.164
Compressed air > 30 min per shift**	53		0.54 ± 0.19		
Cutting tasks involved grinding*	93		0.31 ± 0.13		
II					
Intercept		101.3	−1.84	0.078	0.118
Compressed air > 30 min per shift**	11		0.63 ± 0.17		
Partly open machines**	32		0.31 ± 0.12		
Intercept		102.7	−1.61	0.078	0.120
Compressed air > 30 min per shift**	11		0.57 ± 0.17		
Cutting tasks involved grinding*	51		0.26 ± 0.12		

$^{**}P < 0.01$.

$^{*}P < 0.05$.

between-worker variance. If one operator with very high MWF aerosol exposure (outlier) was excluded, the overall goodness of fit was increased and the determinants of exposure explained 44–45% of the between-worker variance. Since the extracted MWF aerosol concentration was highly associated with the inhalable aerosol concentration, the same determinants applied.

Short-term exposure levels

Personal aerosol measurements with the real-time instrument (DataRAM) with 1 min logging periods showed that the average exposure across companies varied between 0.17 and 0.21 mg m^{-3} with GSDs between 2.17 and 2.46 (Table 5). The maximum concentrations averaged over 1 min periods varied between 2.15 and 5.05 mg m^{-3}, illustrating the presence of peaks. In two companies, the within-worker variance exceeded the between-worker variance. Table 6 describes the results of the mixed-effect model, demonstrating that the use of compressed air and working with partly open machines were important determinants of short-term exposure to aerosols. The use of compressed air explained 32% of the within-worker variance, and compressed air and type of machine together explained ~13% of the between-worker variance.

Within the 2357 short-term measurements, 145 (6.2%) samples exceeded twice the worker's average exposure to the MWF aerosol. Among these peaks, 76% had duration of 1–2 min and 21% a duration of 3–6 min. The contribution of peaks (defined as values more than or equal to twice the mean within respective worker) to the average exposure of individual workers varied from 0 to 70%. On average, 6% of the work time a peak occurred, contributing ~25% to the average concentration. During <4% of the 1-min samples compressed air was used, contributing 8–91% of the average exposure among the nine workers using compressed air. The use of compressed air explained 50% of the variation in peaks across the 21 machine operators. Figure 1 illustrates the highly irregular exposure pattern among a machine operator as a result of using compressed air for cleaning purposes.

Comparisons between different aerosol samplers

A high correlation between inhalable and extracted MWF aerosols was observed ($R^2 = 0.93$) with a regression coefficient of 0.77 (Fig. 2). The comparison between the PAS-6 sampler and the open-faced total dust sampler showed a regression coefficient of 0.50, indicating that the PAS-6 sampler in average will give twice the amount compared to the open-faced dust sampler (Fig. 3).

DISCUSSION

In machine shops using MWFs, the average exposure to inhalable dust ranged from 0.19 to 0.25 mg m^{-3} and ~67% of this exposure consisted of MWF aerosols (extracted amount). The exposure levels of triethanolamine, formaldehyde and volatile compounds were generally low. The between-worker variance could be partly explained by the use of compressed air, working with partly open machines and grinding as cutting task. Peak exposures, especially due to the use of compressed air, contributed substantially to the worker's average exposure. The comparison between the PAS-6 sampler and the open-faced sampler showed that the latter sampler as an average underestimated the dust exposure by a factor 2.

The exposure levels of inhalable aerosols encountered in the Swedish machine shops were comparable to the average exposure level of 0.22 and 0.24 mg m^{-3} in an American survey using a sampler for inhalable particulate mass (Kriebel *et al.*, 1997), but substantially lower than in most other studies (Simpson *et al.*, 2003; Woskie *et al.*, 2003). However, the comparison between studies may be hampered by different sources to the observed exposure levels other than the MWF aerosols, e.g. the co-occurrence of welding activities increased the average exposure to 0.61 mg m^{-3} compared to 0.18 mg m^{-3} in machine shops without welding activities in a Canadian survey (Ross *et al.*, 2004). Hence, it is often preferred to measure the actual MWF aerosol content, expressed by the extractable MWF fraction, or measure the aerosol emanating from the MWF using an elemental marker method (HSE, 2003). In this study, the mean extracted fraction of MWF aerosol was 67% of the inhalable aerosol concentration, which is comparable to the reported mean fraction of 68% in small machine shops in the US (Piacitelli *et al.*, 2001), slightly higher than the elemental marker method (Simpson *et al.*, 2003) but slightly lower than the estimated total extractable MWF fraction of 83–90% to total MWF aerosol by Verma *et al.* (2006). Most of the total aerosol samples (95%) in the Verma study were stationary area samples, which might involve less risk of co-sampled material compared to personal samples.

There was a high correlation between inhalable and extracted MWF aerosols, which indicate that it might be unnecessary to do the extraction step if there are no other dust-generating activities in the machine shop like welding.

The mean values of inhalable aerosols in the three machine shops were well below the Swedish exposure limit value for MWF aerosols (oil mist) of

Table 5. Measurements with DataRAM on 21 machine operators, 1-min samples during ~2 h

Company	*n*	Samples	AM	GM	GSD	Range	wW (%)	bW (%)
1	5	559	0.17	0.10	2.29	0.01–5.05	96	4
2	10	1279	0.21	0.13	2.46	0.01–2.15	42	58
3	6	519	0.21	0.12	2.17	0.03–3.01	76	24

AM, arithmetic mean; GM, geometric mean; wW, within-worker variance; bW, between-worker variance.

1 mg m^{-3} and the National Institute for Occupational Safety and Health recommended TLV of 0.5 mg m^{-3} (NIOSH, 1998). However, in an automobile parts manufacturing plant, clear cross-shift effects on FEV$_1$ were observed among workers using MWFs with exposures above ~0.15 mg m^{-3} (Kriebel *et al.*, 1997). This and the respiratory symptoms reported by Oudyk *et al.* (2003) of operators exposed to MWF aerosols in the range of 0.25–0.84 mg m^{-3} suggest that the current exposure levels of MWF in Swedish machine shops may not prevent the occurrence of respiratory symptoms. The current study shows that the mean exposure may be low, but that during specific activities high peak concentrations may occur. It could be hypothesized that these peaks play an important role in the development of respiratory effects, but since the presence of peaks also largely determined the mean exposure, the relative importance of peaks versus mean exposure is difficult to establish. Cases of hypersensitivity pneumonitis have been observed among operators exposed to high, medium and low levels of MWF aerosols (O'Brien, 2003), and in similar observations in automobile manufacturing plants, the presence of mycobacteria in the MWFs has been put forward as possible explanation for the observed health problems (Gupta and Rosenman, 2006; Robertson *et al.*, 2007). These findings indicate that exposure to MWF aerosols should be held at a minimum, especially when semi-synthetic and synthetic MWFs are used and the MWFs are contaminated with endotoxin and mycobacteria (Gupta and Rosenman, 2006). An efficient maintenance system of the MWFs to remove fine metal particles and tramp oils and to control the amount of bacteria and endotoxins in the fluid is recommended. The machine shops in this study continuously tested the MWF for bacteria and pH and renewed the fluid from twice a year to every second year.

Table 6. Determinants of exposure to aerosols, estimated by mixed-effect models for 1-min samples collected with DataRAM during ~2 h on 21 machine operators

Determinant	Model fit (AIC)	Regression coefficient	wW	bW
Intercept only	4876.5	−2.13	0.445	0.293
Intercept	3961.5	−0.25	0.302	0.256
Use of compressed air**		2.13 ± 0.07		
Partly open machines*		0.44 ± 0.24		

**$P < 0.05$.
*$0.05 < P \leq 0.10$.

In Company 1, where they used recirculating air, the formaldehyde exposure was higher (0.09–0.15 mg m^{-3}) than in the other plants. Triethanolamine was only analysed in the three machine shops, where they used triethanolamine as an additive in the MWFs. The concentrations were quite low with values from 0.002 to 0.036 mg m^{-3}, which are in line with the median concentration of 0.006 mg m^{-3} measured in a Finnish study (Henriks-Eckerman *et al.*, 2007). In total, the triethanolamine concentration comprised 1–19% of the inhalable MWF aerosol with a mean of 6%.

Determinants

Jobs involving cutting tasks, type of operations, enclosure of machines and using compressed air >30 min per shift were significant determinants of exposure, whereas plant was not important. Cutting tasks and operations were highly correlated, which was partly due to the fact that most of the single-operating machines did grinding operations. In

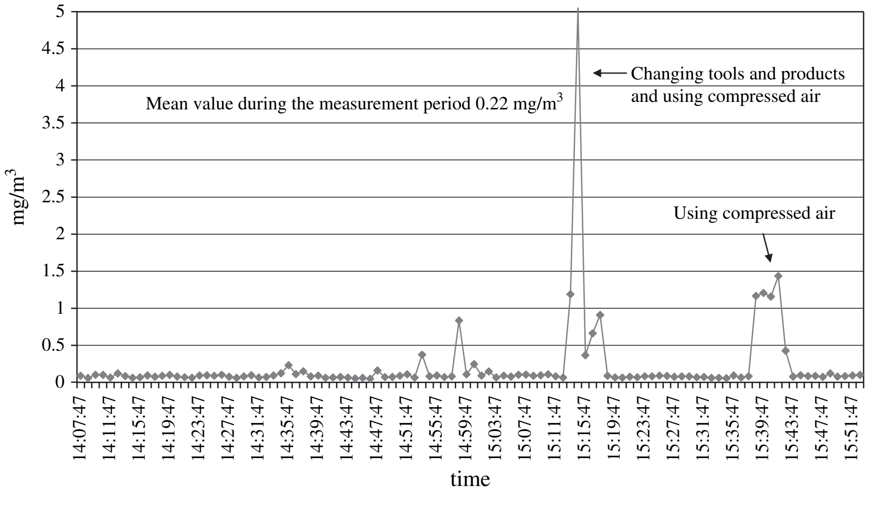

Fig. 1. Turning in an enclosed computer numerical control machine and using compressed air when changing tools and products, as measured with the DataRAM on an operator in machine Shop 1.

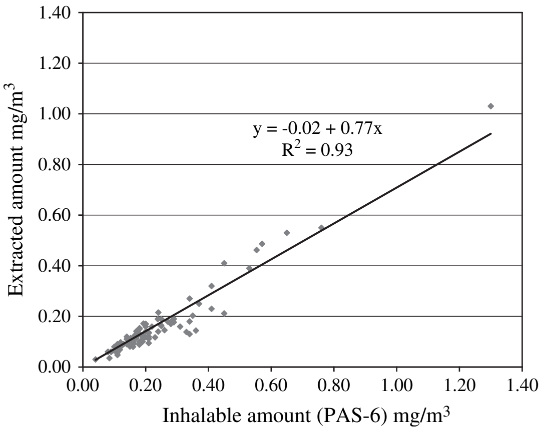

Fig. 2. Correlation between inhalable and extracted MWF aerosol, $n = 95$.

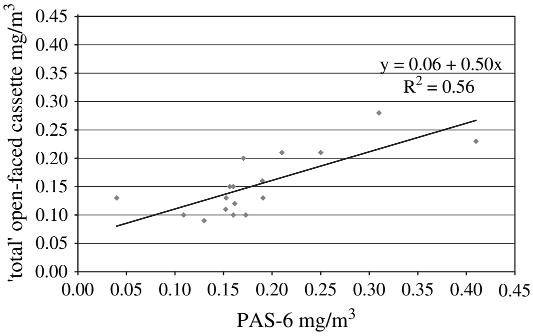

Fig. 3. Correlation between MWF aerosol exposures in parallel sampling of inhalable and total open-faced aerosol, $n = 17$.

addition, cutting tasks and type of machine were also significantly associated since grinding was often done in partly open machines. In the multivariate tests, two alternative models are presented. In the first model, using compressed air >30 min per shift and working with partly open machines were factors significantly associated with increased MWF aerosol exposure and in the second model working with grinding tasks increased the exposure. Number of operators/shift and shop factors like height and volume were quite similar in the different machine shops and were not included in the model. Since inhalable MWF aerosol was highly correlated to the extracted fraction ($R^2 = 0.93$), no separate model was made for the extracted fraction.

The regression coefficient yields a factor with which the background level (intercept) should be multiplied to calculate the estimated geometric mean. For example, an operator working at a partly enclosed machine using compressed air >30 min per shift would have an exposure of inhalable MWF aerosol of $\exp^{(-1.84 + 0.61 + 0.38)} = 0.43$ mg m^{-3} versus $\exp^{(-1.84)} = 0.16$ mg m^{-3} working at and enclosed machine and using compressed air <30 min per shift.

Peak exposure

The number of peaks above twice the average for each measurement period with the real-time instrument differed depending on work tasks. Use of compressed air was the single most important factor. Ten per cent of the values in Fig. 1 (~10 min) were due to the use of compressed air, where these peaks contributed to 62% of the average exposure. At the same time, the maximum value was 5 mg m^{-3} compared to the mean value of 0.22 mg m^{-3}, which shows that the operator can be exposed to peak levels highly exceeding the exposure limit value. Findings of respiratory symptoms reported among operators exposed to MWF aerosols might more depend on peak exposure than average exposure to MWF aerosols (O'Brien *et al.*, 2001).

Comparisons of different methods

In this study, the conical PAS-6 sampler for inhalable dust has been used and in the comparisons the total open-faced dust sampler was used. The seven-hole sampler would have worked as well but the more commonly used IOM sampler for inhalable dust could not be used as the samples collected on filters should be extracted with SFE and the IOM sampler is constructed to sample the aerosol both on the filter and at the walls of the cassette. If there is no need to extract the inhalable aerosol, the IOM sampler can be used as well as any other sampler for inhalable dust.

CONCLUSION

The exposure of inhalable aerosols in three different companies showed very similar arithmetic mean values of 0.19–0.25 mg m^{-3} and relatively low variation as demonstrated in GSDs between 1.56 and 1.79. On average, the extracted fraction of MWF aerosol was 67% of the inhalable aerosol concentration. The correlation between inhalable and extracted aerosol was high (explained variance of 93%), indicating that inhalable aerosol concentrations may be a good, and substantially cheaper, proxy for MWF aerosol levels in situations without other activities giving aerosol exposure, such as welding. The current levels of MWF exposure in Swedish machine shops may not prevent the occurrence of respiratory symptoms. The analysis of determinants of exposure showed that control measures, such as full enclosure of machines and the elimination of the use of compressed air as cleaning technique, are required to reduce the exposure to MWF aerosols to levels below the expected threshold for adverse respiratory health effects.

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