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Determinants of Exposure to Metalworking Fluid Aerosols: A Literature Review and Analysis of Reported Measurements

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An extensive literature review of published metalworking fluid (MWF) aerosol measurement data was conducted to identify the major determinants that may affect exposure to aerosol fractions (total or inhalable, thoracic and respirable) and mass median diameters (MMDs). The identification of determinants was conducted through published studies and analysis of published measurement levels. For the latter, weighted arithmetic means (WAMs) by number of measurements were calculated and compared using analysis of variance and *t*-tests. The literature review found that the major factors affecting aerosol exposure levels were, primarily, decade, type of industry, operation and fluid and engineering control measures. Our analysis of total aerosol levels found a significant decline in measured levels from an average of 5.36 mg m^{-3} prior to the 1970s and 2.52 mg m^{-3} in the 1970s to 1.21 mg m^{-3} in the 1980s, 0.50 mg m^{-3} in the 1990s and 0.55 mg m^{-3} in the 2000s. Significant declines from the 1990s to the 2000s also were found in thoracic fraction levels (0.48 versus 0.40 mg m^{-3}), but not for the respirable fraction. The WAMs for the auto (1.47 mg m^{-3}) and auto parts manufacturing industry (1.83 mg m^{-3}) were significantly higher than that for small-job machine shops (0.68 mg m^{-3}). In addition, a significant difference in the thoracic WAM was found between the automotive industry (0.46 mg m^{-3}) and small-job machine shops (0.32 mg m^{-3}). Operation type, in particular, grinding, was a significant factor affecting the total aerosol fraction [grinding operations (1.75 mg m^{-3}) versus other machining (0.95 mg m^{-3})], but the levels associated with these operations were not statistically different for either the thoracic or the respirable fractions. Across all decades, the total aerosol fraction for straight oils (1.49 mg m^{-3}) was higher than for other fluid types (soluble = 1.08 mg m^{-3}, synthetic = 0.52 mg m^{-3} and semisynthetic = 0.50 mg m^{-3}). Fluid type was also found to be partly associated with differences in the respirable fraction level. We found that the total aerosols were measured by a variety of sampling media, devices and analytical methods. This diversity of approaches makes interpretation of the study results difficult. In conclusion, both the literature review and the measurement data analyzed found that decade and type of industry, operation and fluid were important determinants of total aerosol exposure. Industry type and fluid type were associated with differences in exposure to the thoracic and respirable fraction levels, respectively.

Keywords: enclosure; grinding operation; machining operation; mass median diameters (MMDs); metalworking aerosol fraction; metalworking fluids (MWFs)

INTRODUCTION

Metalworking fluids (MWFs) are generally classified into four types (straight, soluble, synthetic and semi-synthetic) according to the amount and type of oil that they contain. They are extensively used to lubricate, cool the tool–workpiece interface and remove debris from the work surfaces of metal parts that are being drilled, ground, milled or turned in various metalworking operations such as cutting, grinding and metal-forming. MWFs can be delivered to the

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tool–workpiece interface either manually (by brush, spray or dripping) or by an automated system, which includes flooding, misting and high-pressure spray or jet methods. Flooding, in which the fluid is pumped under low-pressure through one or more nozzles directed at the cutting zone, is the most common application method.

Metalworking aerosols, hereafter noted as aerosols, contain fluid mists, vapors, smoke, gases, metallic fines and bioaerosols. These aerosols are dispersed into the air by mechanical forces produced by the moving tools and/or workpieces, condensation of fluid vapors formed by heat in the cutting zone and misdirected or extraneous spraying of fluids directly into the air. Inhalation and dermal exposure can occur during the direct application of the fluid and during set up or removal of the workpieces from the machine spray and from condensation of the aerosol onto the skin. Many factors related to the fluid type, operation and machine characteristics may affect exposure to metalworking aerosols. In addition, engineering control measures such as ventilation, enclosures and guards installed on the metalworking machines affect the amount and size distribution of the aerosols released into the employee's breathing zone.

Various field and laboratory scale studies have been conducted to identify major determinants influencing exposure to metalworking aerosols. An understanding of exposure determinants is important for implementing control measures to reduce aerosol exposures in the current workplace. Determinants can also be used to develop models that predict exposures prospectively or estimate past exposures.

There were two main objectives of this study. The first objective was to identify and describe, through an extensive literature review, exposure determinants of MWF aerosols as identified from comparisons of measurement data within a particular study. A second objective was to compare across studies measurement data to identify determinants through an analysis of reported aerosol levels. The review was done as part of an exposure assessment effort for a population-based case–control study of bladder cancer (D. Baris, M. R. Karagas, C. Verrill, A. Johnson, A. Andrew, C. J. Marsit, M. Schwenn, J. Colt, S. Cherala, C. Samanic, R. Waddell, K. P. Cantor, A. Schned, A. Rothman, J. Lubin, J. F. Fraumeni Jr., R. N. Hoover, K. T. Kelsey and D. T. Silverman, unpublished data).

METHODS

Identification of determinants

Factors affecting aerosol levels were summarized through an extensive literature review of studies reported from before the 1970s through 2007, including one recently published paper from 2008 (Lillienberg *et al.*, 2008). The key words used for literature search were 'metalworking fluids', 'machining fluids', 'cutting oil', 'oil mist', 'coolants', 'metalworking operation', 'machining operation' and 'determinant' which were used singly and in combination. To identify major determinants that may affect either exposure levels by aerosol size fraction or mass median diameters (MMDs), two approaches were used.

First, industrial hygiene study results that evaluated determinants of aerosol fractions and MMDs were summarized. Determinants were identified when investigators reported differences in measurement data associated with possible determinants. This information hereafter is noted as the literature review. Generally these reports were univariate analyses, but four studies reporting multivariate analyses also are described. Personal exposure measurements were the primary type of measurements used for identification of determinants; however, area measurements taken near machining areas were also included. Measurements obtained from direct-reading instruments were excluded.

Secondly, we compiled these published aerosol and MMD exposure measurements and related possible determinants, where provided, into a database. The method to select measurements from the literature was described in detail elsewhere (D. Park, P. A. Stewart and J. B. Coble, accepted for publication). All personal or area airborne measurements taken for at least 1 h were included in the summary statistics regardless of the type of filter or sampling device. Using this information, we analyzed the measurements across studies to identify determinants of aerosol exposure (hereafter noted as the analysis).

For these analyses, few studies described the workplaces in any detail, so the only consistently reported workplace characteristics that were considered as potential determinants were decade, industry, operation and fluid type. Industry was identified as automobile manufacturing, auto part manufacturing and small-job machine shops. Measurement data on other industries were too few for analysis (a total of 254 measurements from five different industries). Operations were categorized as grinding and other machining. Grinding has been distinguished from other metalworking operations based on the type of fluid generally used, the composition of the fluid, the heat generated and the health risks reported (Park *et al.*, 1988; Silverstein *et al.*, 1988; Greaves *et al.*, 1997; Eisen *et al.*, 2001; Park, 2001). All other types of machining were combined because type of machining was often not specified in the published papers. Operations that were specified were drilling (no. of measurements = 134; no. of studies = 4), hardening (n = 36; 1), hobbing (n = 74; 1), sawing (n = 37; 2), stamping (n = 38; 1), milling (n = 272; 3), turning (lathes, screw machine and transfer machine) (n = 347; 4), gear cutting and cutting (n = 1; 2), broaching (n = 16; 1) and salvage (n = 16; 1).

Because of small numbers, these operations were not evaluated separately. Fluid type was frequently identified, and four fluid types (straight, soluble, synthetic and semisynthetic) were evaluated.

Measurements with no information on a particular determinant were excluded from that particular analysis but included in other analyses where determinant information was available. Measurements identified as mixed operations or mixed fluids (Woskie *et al.*, 1996), dry machining (Piacitelli *et al.*, 2001) and non-machining operations such as assembly or inspection (Kenyon *et al.*, 1993; Hallock *et al.*, 1994; Woskie *et al.*, 1996; Hodgson *et al.*, 2001; Piacitelli *et al.*, 2001) were excluded. While identified as determinants in individual studies, engineering controls were not analyzed as determinants across studies because of the lack of sufficient information or measurements for characterizing the control.

In this paper, straight oils are defined as being mineral or other oil-base solutions with no water. Soluble fluids are a combination of mineral oils and emulsifiers (30–85%) that are often sold as concentrates and diluted with water. Synthetic fluids are 70–90% water, with the remainder comprising organic chemicals and additives; they do not contain mineral oils. Semisynthetic fluids are similar to synthetic fluids, but also contain some mineral oils (5–30%). Water-miscible fluids include soluble, synthetic and semisynthetic fluids.

While sampling and analytical characteristics are not determinants of exposure *per se*, the use of different methods can affect the measurement results. There were a variety of methods used to measure MWF aerosols in the literature, so these characteristics also were evaluated, but only for the total aerosol fraction. Sampling durations were categorized as <2 h, 1–7 h, full shift, and 24 h. Sampling type was classified as area, personal, and when identified by the investigators, both (area and personal). Total aerosol levels among sampling collection devices (37-mm filter cassette and impactors), sampling filters (polytetrafluoroethylene (PTFE), glass fiber (GF), mixed cellulose ester (MCE) and polyvinyl chloride (PVC)) and analytical methods (gravimetric and extraction) also were compared.

Three aerosol size fractions were selected for analysis: total (as measured by either a cascade impactor or an open-face cassette), thoracic (i.e. PM_{10} and <9.8 μm, as measured by a cascade impactor) and respirable (i.e. <3.5 μm, as measured by a cascade impactor or cyclone sampler). Aerosol measurements extracted by solvents were excluded, other than for the single analysis described as a sampling and analytic characteristic. The extrathoracic (>9.8 μm), tracheobronchial fraction (<9.8 and >3.5 μm) and $PM_{5.0}$ and $PM_{1.0}$ aerosol fractions were excluded because of small numbers. In addition, determinants for MMDs were evaluated using the same approach as for aerosol exposure levels, i.e. assessing the effect of decade, industry, operation and fluid type.

Statistical analysis

The arithmetic mean (AM) was used for analysis of the measurements as the best summary measure of exposure for epidemiologic studies of chronic disease (Seixas *et al.*, 1988). If only the number of measurements and either a geometric mean (GM) and geometric standard deviation (GSD) or the range was provided, the AM was estimated assuming a log-normal distribution from the GM and GSD (Aitchison and Brown, 1963) or the range (Hein *et al.*, 2008).

When analyzing averages based on different numbers of observations, it is appropriate to weight each average by a weight that is proportional to the inverse of the variance of the mean. Because we did not have variance estimates, weighted arithmetic means (WAMs) were calculated based on the number of measurements reported for each mean.

The distribution of the measurements was found to be positively skewed and approximately log-normal. Consequently, the natural logarithms of the calculated WAM were used for all analyses. Three analyses were conducted for each determinant for total aerosols to determine if there were significant differences in the WAM levels: (i) overall, using a single-factor analysis of variance (ANOVA), (ii) across decades for each determinant category (e.g. auto industry or <2 h duration) using a single-factor ANOVA and (iii) within each decade across determinant categories using a multiple comparison *t*-test. Because of fewer measurements, only an overall single-factor ANOVA was conducted for each determinant for the thoracic and respirable fractions. All statistical analysis was performed using STATA Version 9.0 software (StataCorp, College Station, TX, USA).

RESULTS

Summary of determinants from the literature review

Single determinant analyses. A number of potential determinants have been identified in the published literature (Table 1), although not all the studies reported them as such. Decade was a significant determinant in a study of three large automotive plants between 1958 and 1987. The authors reported a significant decline in total aerosol exposure levels from 1958–1969 (AM = 5.42 mg m^{-3}) to 1970–1974 (2.67 mg m^{-3}), to 1975–79 (2.24 mg m^{-3}) and to 1980–1987 (1.82 mg m^{-3}) ($P < 0.05$) (Hallock *et al.*, 1994). When aerosol concentrations were classified by plant, operation and fluid type, a similar decrease over time was found. Similar trends over time were found for data from two other sources, the National Institute for Occupational Health and Safety (NIOSH) Health Hazard

Table 1. A summary of possible determinants and their associated metalworking aerosol levels, as found in the literature

Determinant		No. of measurements	Mean (mg m^{-3})	Industry type[a]	Fluid type[b]	*P*-value	Reference
Total aerosol fraction including inhalable							
Decade	1958–1969	40	5.42	1	1, 2 and 3	<0.05	Hallock *et al.* (1994)
	1970–1974	74	2.67				
	1975–1979	148	2.24				
	1980–1987	132	1.82				
	1970s	21 plants	1.23	4-1	NI	NI	NIOSH (1998)
	1980s	15 plants	0.57				
	1990s	2 plants	1.00				
	1979–95	NI	0.92	4-2	NI	NI	NIOSH (1998)
	1989–94	NI	0.49				
Industry type	Electrical components (SIC 3643)	15	GM = 1.15	3	A	NI	Piacitelli *et al.* (2001)
	Speed changers (SIC 3566)	55	GM = 0.71				
	Bolts, nuts, screws, rivets and washers (SIC 3452)	34	GM = 0.66				
	Metal-cutting machine tools (SIC 3451)	55	GM = 0.51				
	Other 19 industries	872	GM range = 0.14–0.49				
Location	USA northeast	NI	0.56	3	A	<0.05	Piacitelli *et al.* (2001)
	versus USA west	NI	0.39				
	and versus USA midwest	NI	0.39				
Age of machine	Old machines (≥30 years)	NI	GM = 0.48	3	A	<0.05	Piacitelli *et al.* (2001)
	versus new machines (<10 years)	NI	GM = 0.34				

Table 1. *Continued*

Determinant		No. of measurements	Mean (mg m^{-3})	Industry type[a]	Fluid type[b]	*P*-value	Reference
Operation type	Grinding and	119	GM = 0.67	3	A	<0.05	Piacitelli *et al.* (2001)
	Hobbing	37	GM = 0.60				
	versus other machining operations[c]	741	GM range = 0.27–0.51				
	Grinding	9	0.72	1	1 and 2	NI	Woskie *et al.* (1996)
	Multiple drills	25	0.36				
	Other machining operations[d]	182	0.19–0.24				
	Multiple drills	25	GM = 0.25	1	1 and 2	<0.05	Woskie *et al.* (1996)
	Grinding	9	GM = 0.17				
	Drills	64	GM = 0.16				
	Lathes	61	GM = 0.16				
	Other machining operations[d]	118	GM range = 0.19–0.21				
	Grinding in 1958–1969	7	17.96	1	A	NI	Hallock *et al.* (1994)
	Machining[e] in 1958–1969	25	3.67				
	Grinding in 1970–1979	71	3.44				
	Machining[e] in 1970–1979	128	2.13				
	Grinding in 1980–1987	56	2.28				
	Machining[e] in 1980–1987	61	1.66				
	Grinding	61	0.73	2	2	NI	Simpson *et al.* (2003)
	Multiple operations	42	0.71				
	Other machining operations[d]	188	0.13–0.27				
	Grinding	23	0.49–0.96	1	3 and 4	NI	Kenyon *et al.* (1993)
	Other machining operations[f]	66	0.26–5.99		2, 3 and 4		
	Face grinding	15	0.49	1		NI	Rosenthal and Yeagy (2001)[g]
	Progressive grinding	15	0.77				
	Microcentric grinding	14	0.55				
	Machining on and fluid delivery on	13	0.94[g]	1	2	0.006	Sheehan and Hands (2007)
	Machining off and fluid delivery on	13	0.91[g]			0.006	
	versus machining off and fluid delivery off	13	0.19[g]				

Table 1. *Continued*

Determinant		No. of measurements	Mean (mg m^{-3})	Industry type[a]	Fluid type[b]	*P*-value	Reference
MWF type	Straight and	359	GM = 0.52	3	NA	<0.05	Piacitelli *et al.* (2001)
	Synthetic	106	GM = 0.45				
	versus soluble	242	GM = 0.34				
	and versus semisynthetic	158	GM = 0.33				
	Straight	74	0.24	2		NI	Woskie *et al.* (1996)
	Soluble	139	0.22				
	Straight	45	1.11	2	NA	NI	Simpson *et al.* (2003)
	Water miscible	296	0.67				
Level of engineering control	OEM enclosures with LEV	92	Median = 0.21	1	NI	<0.05	Hands *et al.* (1996)
	versus retrofit enclosures with LEV	213	Median = 0.45				
	and versus little no enclosure	150	Median = 0.48				
	Before upgraded enclosure	11	GM = 2.24[g]	1	2	<0.0001	Sheehan and Hands (2007)
	After upgraded enclosure	11	GM = 0.19[g]				
	New transfer line	18	0.26	1	2	0.003	Sheehan and Hands (2007)
	Old transfer line	18	0.49				
	Old technology (machining)[e]	NI	0.40	1	2	NI	Dasch *et al.* (2005)
	New technology (machining)[e]	NI	0.07		4		
	Old technology (grinding)	NI	1.10		2		
	New technology (grinding)	NI	0.08		1		
	No enclosure or splash	NI	GM = 0.36	3	A	NS	Piacitelli *et al.* (2001)
	versus with splash guard	NI	GM = 0.45				
	OEM splash guards	NI	GM = 0.50			NS	
	versus retrofit splash guards	NI	GM = 0.38				
Thoracic fraction							
Operation type	Grinding	33	GM = 0.36	3	A	NI	Piacitelli *et al.* (2001)
	Hobbing	12	GM = 0.42				
	Other machining operations[c]	278	GM range = 0.13–0.24				
	Case department	215	0.56	1	2	<0.05	Abrams *et al.* (2000)
	Valve body department	145	0.32		2		

Table 1. *Continued*

Determinant		No. of measurements	Mean (mg m^{-3})	Industry type[a]	Fluid type[b]	*P*-value	Reference
Fluid type	Straight	81	GM = 0.27	3	NA	NI	Piacitelli *et al.* (2001)
	Soluble	73	GM = 0.18				
	Synthetic	31	GM = 0.28				
	Semisynthetic	41	GM = 0.23				
Respirable fraction							
Fluid type	Mostly straight	6	0.72[g]	1	NA	NI	Chan and D'Arcy (1990)[g]
	Soluble	10	0.41[g]				
	Synthetic and semisynthetic	6	0.32[g]				
	Semisynthetic	8	0.37[g]				
	Synthetic	8	0.22[g]				
	Straight	9	0.25[g]				
Enclosure and operation	Cam–crank with retrofitted enclosure in spring	150	GM = 0.18[g]	1	NI	NI	Peters *et al.* (2006)[g]
	Cam–crank with retrofitted enclosure in winter	35	GM = 0.20[g]				
	Block-head-rod with new enclosure in spring	178	GM = 0.04[g]				
	Block-head-rod with new enclosure in winter	38	GM = 0.06[g]				

IMIS = Integrated Management Information System, NI = not indicated and NS = not statistically significant.
[a]Industry type: 1 = auto or auto part manufacturing, 2 = UK engineering industry, 3 = small-job machine shop, 4-1 = NIOSH Health Hazard Evaluation US national survey and 4-2 = Occupational Safety and Health Administration IMIS US national survey that NIOSH analyzed.
[b]Fluid type: 1 = straight, 2 = soluble, 3 = synthetic, 4 = semisynthetic and A = all types or not specified.
[c]Turning, sawing, milling, drilling, stamping and mixed operations.
[d]Broaches, chuckers and mixed operations.
[e]Type of machining was not identified.
[f]Turning, milling, drilling and sawing.
[g]Area sample taken near working area

Evaluations and the Occupational Safety and Health Administration's Integrated Management Information System, although the exposure levels differed (NIOSH, 1998) from the study of Hallock *et al.* (1994).

In a study of 79 small-job machine shops located across the USA, four metalworking industries with the highest total aerosol levels (Table 1) were more likely to use straight oils, perform grinding and turning operations and use partially enclosed machines and older machines (mean age of 30 years) than the other non-specified industries in that study. Industries with lower exposures were more likely to use soluble fluids, perform milling and turning operations and use machines that were fully enclosed and newer (mean age, 14 years). There was a difference in levels by geographic region: shops in the northeast, which were associated with the highest aerosol exposure levels, tended to have more machines per shop area and used older machines than in the other regions (data not shown). The GM exposure level for the workers in this study using older machines ($\geq$30 years old) was higher than that of workers using newer machines ($<$10 years old) (GM = 0.48 versus 0.34 mg m^{-3}, respectively) ($P < 0.05$) (Piacitelli *et al.*, 2001).

In general, workers who performed grinding, hobbing (a process used to make gears in which a complex cutting tool and workpiece both rotate) or multiple drilling operations had higher exposure levels than workers of other machining operations. In the study of 79 machine shops, aerosol exposure levels of workers performing grinding and hobbing were statistically similar (GM = 0.67 and 0.60 mg m^{-3}, respectively), but different from all the other machining operations (range 0.27–0.51 mg m^{-3}) ($P < 0.05$) (Piacitelli *et al.*, 2001). The AM for total aerosols at grinders was higher (0.72 mg m^{-3}) than at multiple drills (0.36 mg m^{-3}) and other machining operations (range = 0.19–0.24 mg m^{-3}) (Woskie *et al.*, 1996). Higher levels of aerosol were associated with grinding compared to other types of machining in three automotive manufacturing plants (total) (Hallock *et al.*, 1994), in 24 metalworking industries that were representative of the UK engineering industry (inhalable) (Simpson *et al.*, 2003) and in the otherwise unspecified automotive parts manufacturing industry (inhalable) (Kenyon *et al.*, 1993).

In the study of 79 machine shops, higher total aerosol exposure levels were associated with straight oils (GM = 0.52 mg m^{-3}) and synthetic fluids (GM = 0.45 mg m^{-3}), compared to those of soluble and semisynthetic fluids (GM = 0.34 and 0.33 mg m^{-3}, respectively) ($P < 0.05$) (Piacitelli *et al.*, 2001). However, other investigators have found that workers using straight oils had about the same inhalable aerosol exposure levels as those working with soluble fluids (Woskie *et al.*, 1996), but had higher levels than workers handling unspecified water-miscible fluids (Simpson *et al.*, 2003).

The effect of engineering controls on total aerosol levels has also varied across studies. Originally equipped machines (OEMs) were reported to be associated with significantly lower exposure levels than retrofitted enclosures or machines with few or no enclosures (median = 0.21 versus 0.45 and 0.48 mg m^{-3}, respectively, $P < 0.05$) (Hands *et al.*, 1996). This finding was supported by studies reporting differences before and after upgrades (GM = 2.24 versus 0.19 mg m^{-3}, respectively, $P < 0.0001$), on an old versus new transfer line (0.49 versus 0.26 mg m^{-3}, respectively, $P = 0.003$) (Sheehan and Hands, 2007) and on machines using old versus new technology (Dasch *et al.*, 2005). Another study found no statistically significant effect of splash guards on exposure levels (Piacitelli *et al.*, 2001). In this case, workers operating machines without any type of enclosure or splash guard were exposed to lower aerosol levels (GM = 0.36 mg m^{-3}) compared to workers handling machines with splash guards (GM = 0.45 mg m^{-3}), OEM splash guards (GM = 0.50 mg m^{-3}) or retrofit splash guards (GM = 0.38 mg m^{-3}).

Few studies have investigated single determinants affecting either thoracic or respirable fraction exposure levels. Higher thoracic exposure levels were found to be associated with grinding and hobbing operations than with other machining operations (Piacitelli *et al.*, 2001) and with department (case versus valve, $P < 0.05$) (Abrams *et al.*, 2000). Little difference was found with fluid type (Piacitelli *et al.*, 2001). For the respirable fraction, the effect of fluid type was unclear (Chan and D'Arcy, 1990), but there was a difference between cam–crank operations with a retrofitted enclosure versus block-head-rod operations with new enclosures (Peters *et al.*, 2006).

Multivariate determinant analysis. The effects of specific determinants on aerosol exposure levels summarized above were reported based on univariate analysis without considering other potential determinants. Results of multivariate studies analyzing factors affecting aerosol exposure levels have been reported in four studies (Table 2). In a study of seven classes of determinants on total and thoracic exposure levels in 20 small-job machine shops, factors associated with significantly increased levels of total and thoracic aerosol fractions included the proportion of time spent grinding, operation of an enclosed computer numerical control machine and the presence of welding in the same shop (Ross *et al.*, 2004). Increasing number of machines increased thoracic levels. Factors associated with reduced aerosol exposure levels included the use of a vertical mill (total), machining aluminum (total), milling (thoracic), the shop height (total and thoracic), a shop with a peaked roof (total), the presence of mechanical ventilation (total) and machine tools for which the fluid was periodically changed (total). A significant

Table 2. Summary of factors affecting metalworking aerosol fraction levels using multivariate statistical analysis

Aerosol fraction level, mg m^{-3}	No. of measurements	Independent variables				Statistical model	Reference
		Machine (MT)/ operation type	Engineering control type	MWF type	Other factors		
Ln (total)	161	Grinding, vertical mill (-), aluminum machining (-)	Enclosed CNC, mechanical ventilation (-), LEV¥ (NS)	NS	Presence of welding at shop, shop height (-), peaked roof (-), ventilation (-), machine tools in which fluid is periodically changed (-)	Mixed effect model (R^2 = 0.77)	Ross *et al.* (2004)
Ln (thoracic)	161	Grinding, milling (-)	Enclosed CNC, LEV¥ (NS)	NS	Presence of welding at shop, no. of machines, shop height (-)	Mixed effect model (R^2 = 0.70)	Ross *et al.* (2004)
Ln (thoracic)	403	MT	NS	SS	Plant, FT1*MT	ANOVA (R^2 = 0.46)	Woskie *et al.* (1994a)
Ln (respirable)	403	MT	LEV (-) enclosure (NS)	SS	Plant type, indoor humidity(IH), outdoor temperature (OT), IH*OT, MT*FT2	ANCOVA (R^2 = 0.48)	Woskie *et al.* (1994b)
Ln (inhalable)	93	Grinding	Enclosure	NS	Plant type (NS), type of operation (single or multiple) (NS)	Mixed effect model (R^2 = 0.44–0.45)	Lillienberg *et al.* (2008)

Fluid type (FT1): straight, soluble, synthetic and semisynthetic; FT2: dry, straight (mineral), lapping (mineral), semisynthetic, soluble (emulsion) and synthetic; MT, machine type; CNC = computer numeric controlled; LEV¥ = local exhaust ventilation with no information provided as to the description of the system components such as enclosure, fan and cleaner; ANCOVA, analysis of covariance; NS = not statistically significant; SS = statistically significant. (-) indicates decreased level and '*' indicates interaction effect.

effect for local exhaust ventilation (LEV) and fluid type was not found.

Two multivariate analyses were published that examined aerosol measurements collected at three large automotive plants for determinants affecting either the thoracic (Woskie *et al.*, 1994a) or respirable fraction (Woskie *et al.*, 1994b). Machine type, fluid type, plant type and the interactive term of fluid type and machine type were found to significantly affect the thoracic fraction level (R^2 = 0.46) (Woskie *et al.*, 1994a). The respirable fraction model found that LEV significantly reduced the respirable fraction exposure levels, but no difference was found for enclosure type (none, partial or complete). Machine type, fluid type and plant type were significant factors, as were indoor humidity and outdoor temperature. In addition, the interactions of indoor humidity and outdoor temperature and of machine type and fluid type were significant (Woskie *et al.*, 1994b). Recently, a study of three companies producing alloyed steel, cast iron and aluminum demonstrated that the prolonged use of compressed air, working with partly opened machines, and grinding as a cutting task were important determinants of exposure to inhalable aerosol exposure levels (Lillienberg *et al.*, 2008).

Dermal fluid exposure determinants from the literature review

Most studies of metalworking operations have focused on aerosol exposures. Only two papers were found that examined factors affecting dermal exposure. In the first study, a significant association was found between short cycle time and relative wet time, but machine type was not associated with dermal wetness (Wassenius *et al.*, 1998). In the second study, an association existed between the number of workpieces handled and dermal exposure levels of workers using compressed air to clean workpieces (van Wendel de Joode *et al.*, 2005). In addition, dermal exposure levels of workers operating open machines were found to be significantly higher than those from closed machines.

Identification of determinants by analysis of reported measurements

It was possible to analyze the published total aerosol measurement data only for the determinants of decade, industry, operation and fluid, as well as sampling and analytic characteristics. The number of possible determinants was limited due to insufficient number of measurements and insufficient information about other determinants in the papers.

Sampling and analytical methods. The WAMs for the total aerosol measurements were compared for each sampling and analytic characteristic overall, by decade and by characteristic within decade (Table 3). Overall, there was a significant difference in WAMs

Table 3. Comparison of total aerosol measurements by decade and sampling and analytical method

Classification	<1970s		1970s		1980s		1990s		2000s		*P*-value[a]
	N (*n*)	WAM (SD) ($mg\ m^{-3}$)	*N* (*n*)	WAM (SD) ($mg\ m^{-3}$)	*N* (*n*)	WAM (SD) ($mg\ m^{-3}$)	*N* (*n*)	WAM (SD) ($mg\ m^{-3}$)	*N* (*n*)	WAM (SD) ($mg\ m^{-3}$)	
Sampling duration (*N* = 7654, overall *P*-value[b] = ***)											
<2 h	270 (2)	3.97 (1.0)	-	-	-		-	-	-	-	NA
1–7 h	-	-	157 (1)	5.14 (1.97)	221 (3)	1.64 (1.0)	-	-	386 (2)	0.55 (0.28)	***
Full shift	-	-	-	-	473 (2)	0.27 (0.13)	5531 (6)	0.51 (0.31)	548 (5)	0.56 (0.23)	***
24 h	-	-	-	-	-	-	68 (1)	0.46 (NA)	-	-	NA
P-value[a]		NA		NA		***		NS		NS	
Sample type (*N* = 9379, overall *P*-value = ***)											
Personal	13 (1)	15.9 (NA)	52 (2)	0.96 (1.21)	434 (2)	0.26 (0.24)	5854 (8)	0.50 (0.31)	299 (5)	0.57 (0.30)	***
Area	294 (3)	4.93 (3.71)	184 (3)	4.46 (2.51)	260 (3)	1.45 (1.0)	89 (2)	0.45 (0.04)	517 (3)	0.55 (0.16)	***
Both	-	-	603 (1)	2.19 (0.96)	411 (1)	1.87 (0.38)	75 (1)	0.77 (1.33)	294 (1)	0.63 (0.35)	***
P-value		NS		NS		***		NS		NS	
Sampling device (*N* = 7957, overall *P*-value = NS)											
Filter cassette	270 (2)	3.97 (1.0)	209 (2)	4.10 (2.58)	173 (3)	1.74 (1.04)	5015 (5)	0.49 (0.23)	984 (6)	0.55 (0.23)	***
Impactor[c]	-	-	-	-	521 (2)	0.37 (0.44)	659 (4)	0.67 (0.75)	126 (3)	0.78 (0.12)	***
P-value		NA		NA		***		NS		*	
Filter type (*N* = 7957, overall *P*-value = NS)											
GF	270 (2)	3.97 (1.0)	170 (2)	4.88 (2.11)	602 (4)	0.67 (0.88)	970 (1)	0.52 (0.30)	-	-	***
PVC	-	-	39 (2)	0.72 (1.46)	-	-	34 (1)	0.14 (0.06)	377 (3)	0.56 (0.18)	***
PTFE	-	-	-	-	-	-	4633 (6)	0.51 (0.35)	733 (5)	0.58 (0.26)	NS
MCE	-	-	-	-	92 (1)	0.96 (0.83)	37 (1)	0.52 (NA)	-	-	NS
P-value		NA		**		NS		NS		NS	
Analytical method (*N* = 9379, overall *P*-value = **)											
Gravimetric	285 (2)	5.62 (4.58)	643 (3)	2.12 (1.04)	932 (3)	1.02 (0.86)	3191 (10)	0.56 (0.31)	755 (8)	0.59 (0.21)	***
Extraction	22 (1)	2.39 (0.72)	196 (3)	4.23 (2.62)	173 (3)	1.74 (1.04)	2827 (5)	0.44 (0.29)	355 (2)	0.54 (0.31)	***
P-value		NS		NS		NS		***		NS	

P-value = ANOVA (dependent variable = log-transformed level), *$0.05 < P < 0.10$; **$0.01 < P < 0.05$; ***$P < 0.01$; NS, not statistically significant; NA, not applicable because category of studies = 1; *N* (*n*), number of measurements, (no. of studies); '-', no measurements.
[a]*P*-values of multiple comparison *t*-test in the classification within decade or among decades.
[b]*P*-value of ANOVA evaluating differences in the classification across decades.
[c]Includes open-filter cassette.

by sampling duration, with shorter sampling periods resulting in higher levels (<2 h = 3.97 mg m^{-3}, 1–7 h = 1.80 mg m^{-3}, full shift = 0.47 mg m^{-3} and 24 h = 0.46 mg m^{-3}, $P \leq 0.0001$). Both 1–7 h and full-shift durations showed significant differences in WAMs across decades, ($P \leq 0.0001$ and $P = 0.0034$, respectively). Within decades, a significant difference in WAMs by duration was only seen in the 1980s: the WAM for 1–7 h was higher than that for full-shift measurements ($P \leq 0.01$).

Trends for sample type (personal, area and both) were similar to those of sampling duration. Overall, sample type resulted in significantly different WAMs (personal = 0.52 mg m^{-3}, area = 2.21 mg m^{-3} and both = 1.68 mg m^{-3}, $P \leq 0.001$). There were also significant differences in the WAMs across decades for each type. Only in the 1980s, however, was a significant difference found within a decade among sample types, with the WAM of both sample types combined being significantly higher that that of either personal ($P \leq 0.0001$) or area ($P = 0.041$) measurements. In addition, the WAM for area samples was significantly higher than that for personal samples ($P \leq 0.0001$) (data not shown).

There was no overall difference in total aerosol levels as measured by a closed-filter cassette (0.78 mg m^{-3}) or an open-faced filter (0.56 mg m^{-3}) ($P > 0.05$). There were significant differences among the WAMs across decades. Again, in the 1980s, there was a significant difference between the WAMs of the two methods ($P = 0.0001$), but there was also a significant difference in the 2000s ($P = 0.0141$).

There were no overall differences by filter type ($P = 0.0996$), but the WAMs from GF filters and from PVC filters showed significant differences across decades ($P \leq 0.0001$ and $P = 0.0079$, respectively). The only difference between any of the filter types for the same decade was in the 1970s when the average aerosol level collected on GF filters was significantly higher than the level on PVC filters ($P = 0.0032$).

The average level quantified by the gravimetric method (1.00 mg m^{-3}) was found to be significantly higher than by the extraction method (0.72 mg m^{-3}) ($P = 0.0071$). There were significant differences for each method across decades ($P = 0.0293$ and $P \leq 0.0001$). The only difference within a decade was in the 1990s, when the gravimetric method was higher than the extraction method ($P = 0.0082$). The means of the gravimetric and extraction methods were compared based on the fluid type (data not shown). Except for soluble fluids, the averages of the aerosol measurements quantified by the gravimetric method for the other three fluid types were higher than those by the extraction method; for semisynthetic fluids, the difference was significant ($P = 0.0001$).

Total aerosol analysis. The WAMs for total aerosols were significantly different across decades, industries, operations and fluids (Table 4). Aerosols measured prior to the 1970s (5.36 mg m^{-3}) were significantly higher than those during 1970s (2.52 mg m^{-3}) and both were significantly higher than the levels in later decades (0.50–1.21 mg m^{-3}) ($P < 0.001$).

The WAMs for the automotive (1.47 mg m^{-3}) and auto parts (1.83 mg m^{-3}) industries over all decades were not significantly different, but both were significantly higher than the WAM for small-job machine shops (0.68 mg m^{-3}, $P \leq 0.001$). The mean exposure levels for the auto part industry were generally higher than those for the auto and small-job machine industries for each decade, but these differences were not significant. In the 1990s, there was a marginally significant difference between the auto industry (0.98 mg m^{-3}) and small-job machine shops (0.49 mg m^{-3}) ($P = 0.09$).

When all measurements were combined into grinding or machining operations, regardless of decade or industry, a significant difference was found (1.75 mg m^{-3} for grinding and 0.95 mg m^{-3} for machining, $P = 0.002$). The WAM from grinding operations was higher than that from machining operations for each decade, except for <1970s when the grinding WAM was 3.05 mg m^{-3} and the machining WAM was 12.92 mg m^{-3}. The differences were not significant; however, for any decade, except in the 1990s (0.77 versus 0.47 mg m^{-3}, respectively, $P = 0.006$).

Significant differences in WAMs were found by fluid type. Overall, aerosol levels from straight oils were associated with a significantly higher WAM (1.49 mg m^{-3}) than those from synthetic (0.52 mg m^{-3}) and semisynthetic fluids (0.50 mg m^{-3}, $P = 0.017$), but the results were inconsistent by decade. In the 1970s, soluble fluids (4.07 mg m^{-3}) were associated with a marginally significantly higher average aerosol exposure level than straight oils (1.86 mg m^{-3}, $P = 0.062$). In the 1990s, the WAM for straight oil aerosols (0.71 mg m^{-3}) was significantly higher than that for soluble (0.47 mg m^{-3}, $P = 0.063$) and semisynthetic fluids (0.36 mg m^{-3}, $P = 0.069$), but not for synthetic fluids (0.51 mg m^{-3}). During the 2000s, the WAM for semisynthetic aerosols (0.70 mg m^{-3}) was statistically higher than that of soluble fluids (0.42 mg m^{-3}, $P = 0.005$), but it was not statistically different from that of straight oils (0.61 mg m^{-3}).

When aerosol measurements from synthetic, soluble and semisynthetic fluids were all grouped into water-miscible fluids since the 1980s, the trend in the WAMs between aerosol levels for the two fluid groups was found to be similar to that seen in the four fluid groups analysis. The overall WAM for straight oil aerosols (1.49 mg m^{-3}) was significantly

Table 4. Comparison of WAMs for total metalworking aerosol by decade, industry, operation and fluid type

Decade	Industry type	Operation type	Fluid type	No. of measurements	WAM (mg m^{-3})	SD (mg m^{-3})	Multiple mean comparison test[a]	P-value[b]
<1970s	All	All	All	311	5.36	4.28	a	<0.001
1970s	All	All	All	874	2.52	1.76	b	
1980s	All	All	All	1085	1.21	0.93	c	
1990s	All	All	All	6002	0.50	0.31	c	
2000s	All	All	All	1107	0.55	0.19	c	
All	Auto	All	All	1775	1.47	1.10	a	<0.001
All	Auto part	All	All	1126	1.83	3.16	a	
All	Small jobs	All	All	4751	0.68	0.84	b	
All	All	Grinding	All	1005	1.75	1.84	a	0.002
All	All	Machining	All	3583	0.95	1.71	b	
All	All	All	Straight	1406	1.49	1.45	a	0.017
All	All	All	Soluble	2233	1.08	1.50	NS	
All	All	All	Synthetic	321	0.52	0.14	b	
All	All	All	Semisynthetic	551	0.50	0.20	b	
All	All	All	Water miscible	3105	0.92	1.30	b	
<1970s	Auto part	All	All	63	10.26	7.60	NS	NS
<1970s	Small jobs	All	All (straight)	248	4.11	0.95		
<1970s	All	Grinding	All	17	3.05	NA	NS	NS
<1970s	All	Machining	All	46	12.92	7.08		
<1970s	All	All	Straight	257	4.01	1.04	NS	NS
<1970s	All	All	Soluble	17	3.05	NA		
1970s	Auto	All	All	627	2.11	1.00	NS	NS
1970s	Auto part	All	All	211	4.09	2.56		
1970s	All	Grinding	All	259	3.80	2.62	NS	NS
1970s	All	Machining	All	369	1.86	0.99		
1970s	All	All	Straight	112	1.86	1.44	a	0.062
1970s	All	All	Soluble	281	4.07	2.05	b	
1980s	Auto	All	All	988	1.15	0.93	NS	NS
1980s	Auto part	All (machining)	All (soluble)	92	1.73	0.92		
1980s	All	Grinding	All	161	1.94	0.73	NS	NS
1980s	All	Machining	All	653	1.40	0.91		
1980s	All	All	Straight	176	1.40	1.23	NS	NS
1980s	All	All	Soluble	387	1.29	0.98		
1980s	All	All	Synthetic	25	0.66	0.09		
1980s	All	All	Semisynthetic	16	0.71	NA		
1990s	Auto	All	All	127	0.98	1.46	a	0.092
1990s	Small jobs	All	All	4503	0.49	0.16	b	
1990s	All	Grinding	All	334	0.77	0.17	a	0.006
1990s	All	Machining	All	2472	0.47	0.40	b	
1990s	All	All	Straight	845	0.71	0.22	a	
1990s	All	All	Soluble	1382	0.47	0.55	b	
1990s	All	All	Synthetic	296	0.51	0.14	NS	
1990s	All	All	Semisynthetic	326	0.36	0.09	b	
2000s	Auto	All (machining)	All (semisynthetic)	33	0.70	NA	NS	NS
2000s	Auto part	All	All	760	0.51	0.15		
2000s	All	Grinding	All	234	0.66	0.16	NS	NS
2000s	All	Machining	All	43	0.63	0.17		
2000s	All	All	Straight	16	0.61	NA	NS	0.005
2000s	All	All	Soluble	166	0.42	0.12	a	

Table 4. *Continued*

Decade	Industry type	Operation type	Fluid type	No. of measurements	WAM (mg m^{-3})	SD (mg m^{-3})	Multiple mean comparison test[a]	*P*-value[b]
2000s	All	All	Semisynthetic	209	0.70	0.13	b	
All	All	All	All	9379	0.94	1.41		

NA: not applicable because number of studies = 1. The number of measurements across subcategories may not equal the total number of measurements for any particular category because means are not presented when information on a subcategory was not provided.
[a]Multiple mean comparison *t*-test; different letters indicate significant differences, 'NS' indicates no statistically significant differences with any other groups.
[b]ANOVA (dependent variable = log-transformed value).

higher than the WAM for water-miscible fluid aerosols (0.92 mg m^{-3}, $P = 0.002$). In particular, significantly higher aerosol levels were found for straight oils (0.71 mg m^{-3}) than for water-miscible fluids (0.46 mg m^{-3}, $P = 0.005$) in the 1990s (data not shown).

Thoracic and respirable aerosol analysis. The overall trends observed for the thoracic and respirable fraction levels were different from those found for total aerosols, as indicated in Table 5. No significant difference between decades was found for the thoracic fraction, although the mean thoracic level in the 2000s (0.40 mg m^{-3}) was marginally lower than that in the 1990s (0.48 mg m^{-3}, $P = 0.063$). Further analyses were performed to examine exposure differences among industry, operation and fluid types based on decade (data not shown). The thoracic WAM for the automotive industry (0.46 mg m^{-3}) was significantly higher than that for small-job machine shops (0.32 mg m^{-3}) ($P = 0.007$), but not for auto parts (0.35 mg m^{-3}). Operation was not a significant variable for thoracic fraction; however, a marginally significant difference was also found in the 1990s ($P = 0.088$) (data not shown). Significant differences in thoracic exposure levels were not found among the fluid types.

Significant differences in respirable fraction levels were not found for any categories except for fluid type. The overall WAMs for straight (0.34 mg m^{-3}) and soluble aerosols (0.56 mg m^{-3}) were higher than that for synthetic aerosols (0.21 mg m^{-3}) ($P = 0.088$ and $P = 0.002$, respectively). In the 1990s, the mean for soluble fluid aerosols (1.53 mg m^{-3}) was significantly higher than that for semisynthetic (0.26 mg m^{-3}) and synthetic fluid aerosols (0.27 mg m^{-3}) ($P \leq 0.0001$) (data not shown).

MMDs analysis. The WAMs of MMDs ranged from 4.2 to 6.6 μm (Table 6). The MMD of aerosols from grinding was marginally higher than that from machining ($P = 0.078$), in particular, when grinding versus machining with semisynthetic fluids ($P = 0.026$). For decade, industry and fluid type, differences were not significant.

DISCUSSION

Factors affecting exposure to MWF were identified through an extensive literature review and through an analysis of published measurements. We found that decade, industry type, operation type, fluid type and type of engineering control (LEV, enclosure, etc.) were significantly associated with aerosol exposure levels of metalworking operations.

Decade was found to be a highly significant factor. The total aerosol exposure levels prior to 1970s and in the 1970s were significantly higher than those in the 1980s, 1990s and 2000s. This decline most likely reflects changes in machining operations, fluid types and engineering control measures over the years. For example, during the 1970s and 1980s, many US plants installed recirculating air cleaners, improved recirculating air filtration systems and renovated working conditions (Calvert *et al.*, 1998). Other changes in aerosol levels may have been due to installation of enclosures, LEV on machines (Hallock *et al.*, 1994) and technological advances in machine tools. For the thoracic fraction, no measurements were available prior to the 1990s when total aerosol levels were relatively high. The mean thoracic fraction in the 1990s was not significantly different from that of the 2000s, a pattern similar to what was seen for total aerosol exposures. Piacitelli *et al.* (2001) found that thoracic fraction levels measured in the 1990s followed the same relationships for operation and fluid types as seen for total aerosol exposures, so it is likely that historical thoracic levels were much higher. WAMs for the respirable fraction did not significantly change from the 1980s to the 1990s. It is unclear whether this finding is an artifact or whether the exposure levels did not change.

Type of industry significantly affected total and thoracic, but not respirable, aerosol fractions. To date, no study has reported a comparison of aerosol levels in different manufacturing industries. Our

Table 5. Comparisons between thoracic and respirable fraction by decade, industry, operation and fluid types

Classification		Thoracic			Respirable		
		No. of measurements	WAM (mg m^{-3})	SD (mg m^{-3})	No. of measurements	WAM (mg m^{-3})	SD (mg m^{-3})
Decade	1980s				131	0.32	0.10
	1990s	1968	0.48	0.21	102	0.33	0.43
	2000s	4663	0.40	0.15	37	0.27	NA
	P-value		0.063			NS	
Industry type	Auto	4788	0.46	0.18	233	0.32	0.29
	Auto part	439	0.35	0.07	37	0.27	NA
	Small-jobs	1384	0.32	0.07			
	P-value		0.007			NS	
Operation type	Grinding	231	0.48	0.19	36	0.22	0.04
	Machining[a]	5805	0.43	0.18	197	0.34	0.32
	P-value		NS			NS	
Fluid type	Straight	1599	0.46	0.17	39	0.34	0.2
	Soluble	1810	0.43	0.20	53 (42[b])	0.56 (0.31[b])	0.61 (0.08[b])
	Synthetic	758	0.40	0.05	119	0.21	0.07
	Semisynthetic	55	0.31	0.09	16	0.31	0.07
	P-value		NS			0.0234 (0.0329)	
All	All	6631	0.43	0.17	270 (216[b])	0.31 (0.11[b])	0.27 (0.11[b])

P-value, ANOVA (dependent variable = log-transformed value. NA: not applicable because category of studies = 1, NS: not statistically significant.
[a]Includes milling, drilling, hobbing, tapping, broaching, turning, stamping.
[b]Result obtained after unexpected high level (1.53 mg m^{-3}) is excluded.

Table 6. MMDs by decade, industry, operation and fluid type

Classification		No. of measurements	MMD (μm)	SD (μm)	*P*-value[a]
Decade	1990s	315	5.6	0.9	NS
	2000s	260	5.4	1.2	
Industry type	Auto	315	5.6	0.9	NS
	Small-jobs	260	5.4	1.2	
Operation type	Grinding	117	6.1	1.0	0.078
	Machining[b]	458	5.3	1.0	
Fluid type	Straight	237	5.5	1.2	NS
	Soluble	206	5.7	0.7	
	Synthetic	81	5.8	1.2	
	Semisynthetic	51	4.2	0.9	
Straight	Grinding	16	6.5	2.5	NS
	Machining[b]	221	5.4	1.1	
Soluble	Grinding	57	6.6	0.5	NS
	Machining[b]	149	5.3	0.3	
Synthetic	Grinding	30	5.4	0.4	NS
	Machining[b]	51	6.0	1.4	
Semisynthetic	Grinding	14	5.1	0.9	0.026
	Machining[b]	37	3.8	0.6	
Total		575	5.5	1.1	

NS = not statistically significant.
[a]Includes milling, drilling, hobbing, tapping, broaching, turning and stamping.
[b]*P*-value, ANOVA (dependent variable = MMDs).

analysis for total aerosols found that the means associated with the auto and auto part industries were generally higher than those from small-job machine shops, but the differences between the means of the two auto industries were not significant. There was also a significant difference between the auto and small-job industries for the thoracic fraction. In addition, a significant difference among industry groups within the small machine shop category was reported (Piacitelli *et al.*, 2001). Small-job machine shops tend to be owner-operated or small businesses and typically involve smaller buildings with fewer machines and workers than automotive plants (Piacitelli *et al.*, 2001; Ross *et al.*, 2004). The former generally use much lower quantities of MWFs and are more likely to machine a variety of products and therefore frequently change machining parameters. In addition, one-third of the 942 small-shop machinists monitored were reported to machine with equipment at least 30 years old. The average machining speed of the new machines was two times higher than for the machines ≥30 years (Piacitelli *et al.*, 2001), and as aerosol generation increases dramatically with machine-rotating speed (Heitbrink *et al.*, 2000a; Thornburg and Leith, 2000a; Dasch *et al.*, 2001), the presence of many old machines with lower machining speeds in small-job machine shops may be one explanation for the lower exposure levels than in the auto and automotive industries. Other possible reasons for the differences in levels is that machines handling larger production volumes (in larger companies) may have less efficient controls, especially if there are many machines in large departments. Grinding and other high emitting operations also could be more common in large companies compared with small-job machine shops. More information on exposures is needed for other major metalworking industries.

Both the literature review and our analysis found that operation type, in particular, grinding, was a significant factor affecting the total (Ross *et al.*, 2004) and thoracic fractions (Woskie *et al.*, 1994a; Ross *et al.*, 2004). Average measurements from both grinding and machining operations followed the overall pattern of a decline over time. Determinants associated with metalworking operations include not simply machine type but also operational parameters related to fluid application rate, i.e. fluid velocity and flood versus through-tool application (Heitbrink *et al.*, 2000a; Thornburg and Leith, 2000a; Dasch *et al.*, 2002; Wang *et al.*, 2005), pressure (Heitbrink *et al.*, 2000b), machine-rotating speed (Heitbrink *et al.*, 2000a; Thornburg and Leith, 2000b; Rosenthal and Yeagy, 2001; Wang *et al.*, 2005), tool diameter and feed (Dasch *et al.*, 2002), cut depth (Thornburg and Leith, 2000a; Dasch *et al.*, 2002; Michalek *et al.*, 2003) and tool wear (Dasch *et al.*, 2002). Grinding and turning produces the largest particles, whereas hobbing results in the smallest (Piacitelli *et al.*, 2001). Higher machining speeds generate higher emissions than lower speeds, in that mist generation increases as the square of the machine-rotating speed (Thornburg and Leith, 2000a). Because of the large variability among machine operation parameters, it was not feasible to quantify the relationship of these various parameters or to identify the most important in this analysis. In the future, metalworking operations, especially grinding operations, should be evaluated to ensure that exposure levels are controlled. Our analysis did not find operation to significantly affect respirable levels, although others reported this finding (Woskie *et al.*, 1994b). More information is also needed on exposure levels associated with other types of machining.

The effect of fluid type on aerosol exposure levels is unclear. Differences in levels by fluid type reported in the engineering literature were not observed in the industrial hygiene literature, although total aerosol exposure levels from straight oils were generally higher than those of other fluid types. Woskie *et al.* (1994b) found that straight oil aerosol exposure levels were significantly higher than those from water-miscible fluids for not only large particles (>9.8 μm) but also for the respirable aerosol fraction level. Experimental studies have found straight oils resulted in higher aerosol levels (Dasch *et al.*, 2002), but among the water-miscible fluids, the findings have again been inconsistent (Turchin and Byers, 2000). Higher aerosol levels may be generated from straight oils because they are 100% oil, as opposed to water-miscible fluids, which have far less oil and more water (Dasch *et al.*, 2002). Because the water is lost to evaporation, these fluids produce smaller aerosols and may result in lower exposure levels (Dasch *et al.*, 2005). Increasing the amount of water in the fluid, therefore, could provide a relatively inexpensive way to reduce aerosol exposure levels. Straight oils also may be associated with high aerosol levels because these oils may be used more frequently in older machines that may be less likely to have exposure control measures. Other contributors to the inconsistent results may be other fluid components, contamination by other particles in the workplace, volatility (Dasch *et al.*, 2005), age, temperature (Dasch *et al.*, 2002) and tramp oil level (Turchin and Byers, 2000; White and Lucke, 2003).

The effect of engineering controls on aerosol levels also varied. OEM enclosures with unspecified LEV (Hands *et al.*, 1996; Piacitelli *et al.*, 2001) and enclosures without LEV (Lillienberg *et al.*, 2008) were significantly associated with a reduction in aerosol exposure levels in some studies. The presence of enclosures without LEV, however, also was found not to have a significant effect (Piacitelli *et al.*, 2001). Unspecified LEV (without enclosures) has been associated with a decrease in small particles (<3.5 μm) (Woskie *et al.*, 1994b) and an increase in total and thoracic aerosol levels (Ross *et al.*, 2004). There may be several reasons for these unexpected findings. First, controls may more often have been used on machines most likely to generate the highest MWF emissions, but the efficiency of the controls may be limited, so that the use of controls may still be associated with higher levels than machining operations without controls (Hands *et al.*, 1996). Enclosures may leak or excessive exposure may occur when parts are taken out of machines (Ross *et al.*, 2004). Also, enclosures may require cleaning of the insides, which could be done with compressed air. If this practice does occur, it could be result in higher exposure levels than operations without enclosures (Lillienberg *et al.*, 2008). Second, there may have been a variety of machines located in close proximity to each other that were concurrently performing different types of operations and using different parts, metals, fluids and engineering controls (Piacitelli *et al.*, 2001). Machines with no enclosures might be adjacent to machines with a full enclosure. In this case, the MWF aerosols generated from any particular machine most likely would become quickly mixed with aerosols from the surrounding machines, some of which may not have been controlled, resulting in fairly homogeneous MWF aerosol levels throughout the area. In addition, the level of engineering controls affected aerosol fraction levels and characteristics in automobile plants. New technology controls (enclosed and vented machines) were associated with lower concentrations, and the primary mode shifted to smaller particles (Dasch *et al.*, 2005). The larger particle mode ($>$20 μm) disappeared when grinding with new technology controls. Thus, the technology was more effective for larger particles than for smaller particles (Dasch *et al.*, 2005). Although an effect was reported for various types of engineering controls on total aerosol exposure levels (Hands *et al.*, 1996; Piacitelli *et al.*, 2001; Dasch *et al.*, 2005; Sheehan and Hands, 2007), the number of aerosol exposure measurements with same (or similar) engineering control type in these studies was insufficient to allow us to conduct a meaningful analysis.

The aerosol levels presented here, in particular those for total aerosol, were measured by a variety of sampling media, devices and analytical methods. This diversity makes interpretation of the study results difficult, particularly when not all media or methods were used in all decades. Some patterns emerged from these analyses, however. Use of glass fiber filters was associated with significantly higher total aerosol levels than PVC filters in the 1970s. The significant differences among filter types reported from several experimental studies (McAneny *et al.*, 1995; Leith *et al.*, 1996; Volckens *et al.*, 1999; Volckens *et al.*, 2000) were not found in our analyses, which may, in part, be reflecting the differences in filter types used over the years. In the 1980s, total aerosol levels were found to be higher for short-term and area (versus longer-term and personal) measurements and with the use of cassettes compared with impactors. Means measured since the 1990s by a cascade impactor were found to be slightly higher than those measured by 37-mm closed-filter cassettes, which is in agreement with other published findings (Wilsey *et al.*, 1996; Rosenthal and Yeagy, 2001; Lillienberg *et al.*, 2008). Thus, the 1980s findings might be confounded by the duration or type of measurement.

The effect of the collection device on exposure levels is unclear. Lillienberg *et al.* (2008) reported that the average of aerosol levels collected by an inhalable aerosol sampler (a Dutch PAS-6 sampler), on average, was twice as high as that of the open-faced sampler. The difference we found between the cascade impactors and closed-filter cassettes ($\sim$1.4) is lower than the factor of 3 reported as the relationship between Institute of Occupational Medicine (IOM) samplers and the closed-filter cassettes (Wilsey *et al.*, 1996). Another device for inhalable aerosols, the IOM sampler, also has been found to collect more aerosol than the 37-mm closed-cassette sampler (Rando *et al.*, 2005). That is, for both these samplers, the inhalable aerosol exposures were systematically higher than what has been regarded as 'total' aerosol. This difference among sampling types (filter cassettes, impactors and IOMs) in collecting total or inhalable aerosols should be considered when factors are being used to convert total levels to either thoracic or respirable aerosol concentrations.

This review was limited in several ways. First, we found descriptions of the working conditions (e.g. operation and fluid type, as well as workplace and job characteristics) often limited. About 45% of all measurements reported did not specify the operation or fluid type (D. Park, P. A. Stewart and J. B. Coble, accepted for publication). In particular, even when machining was identified as the operation, the specific type of machining was not identified. There are almost 20 types of machining operations (milling, drilling, turning, lapping, cutting, etc.), so that combining measurement data across operations without considering the variance within or between operations was likely to have resulted in an imprecise mean. Second, many determinants identified were evaluated singly, without consideration of other determinants. Thus, some determinants identified (in particular, decade) may be reflecting other determinants, but this hypothesis could not be evaluated because no information on other possible determinants was provided. Furthermore, for some analyses, few measurements were available. For example, there were no thoracic measurements before the 1990s. As well, sampling and analytic differences may have confounded some of the results. In addition, the only statistic considered in this analysis was the means. The standard deviations of the measurements from each study were not incorporated into our analyses because it was not always provided. Use of the WAMs was likely to result in less variance compared with an analysis of individual measurements. Finally, in order to estimate the combined effects on aerosol exposure levels of the potential determinants identified here, multivariate analyses would be required.

These limitations make it difficult to evaluate the accuracy of the predicted exposure levels for any particular situation.

Little information was found on dermal exposures, although skin exposure to MWFs can vary considerably among machine operators (Wassenius *et al.*, 1998). Identification of the number of workpieces handled as an exposure determinant (van Wendel de Joode *et al.*, 2005) is supported by the relation between exposure level and cycle time, as machines with shorter cycle times generally result in a higher number of workpieces handled by a worker (Wassenius *et al.*, 1998). More work should be done on investigating determinants of dermal exposure.

Most epidemiological studies of the cohort design investigating cancer and respiratory disease risks have been conducted in large automobile plants (Tolbert *et al.*, 1992; Eisen *et al.*, 1994; Bardin *et al.*, 1997; Schroeder *et al.*, 1997; Sullivan *et al.*, 1998; Zeka *et al.*, 2004; Agalliu *et al.*, 2005; Bardin *et al.*, 2005; Thompson *et al.*, 2005; Malloy *et al.*, 2007). Yet 70–80% of all workers in USA exposed to MWFs work in small-job machine shops (Eisen *et al.*, 1997; Piacitelli *et al.*, 2001). Only a few studies have measured exposure levels in such workplaces (Ely *et al.*, 1970; Kennedy *et al.*, 1999; O'Brien *et al.*, 2001; Piacitelli *et al.*, 2001; Ross *et al.*, 2004). Information useful for investigating health risks in population-based epidemiological studies for the many subjects who work in small-job machine shops has been limited, so that our analysis may provide a basis for investigating health risks in these workplaces. In the case–control study for which these data were evaluated, information was collected for all jobs on job title, industry and start and stop dates. For machinists and other jobs that may do machining, e.g. mechanics, additional information on the type of operation and fluid type was often collected. The measurement data presented here found that date, industry, type of operation and fluid type were important determinants of total aerosol exposure. Combining the job information from the case–control study, therefore, with the measurement information presented here will allow estimation of machinists' exposure to total aerosol levels in the case–control study.

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