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Exposures to Inhalable and "Total" Oil Mist Aerosol by Metal Machining Shop Workers

Several recent studies have compared worker personal aerosol exposures as measured by the current method with those obtained by a new approach based on collecting the inhalable fraction, intended to represent all the particles that are capable of entering through the nose and/or mouth during breathing. The present study investigated this relationship for a metal machining facility where aerosols were generated from severely refined, nonaqueous ("straight") cutting oils used during the lathe working of metal rod stock. Workers (n=23) wore two personal aerosol samplers simultaneously, one of the 37-mm type (for "total" aerosol exposure, E_{37}) and the other of the Institute of Occupational Medicine (IOM) type (for inhalable aerosol exposure, E_{IOM}). The data were analyzed by weighted least squares linear regression to determine the coefficient S in the relation $E_{IOM} = S{\bullet}E_{37}$. It was found that $S=2.96\pm0.60$. This ratio—in which exposure to inhalable aerosol was greater than to "total" aerosol—is consistent with previous observations in other industries. The relative coarseness of the oil mist aerosol, as estimated by cascade impactor measurements, probably explains the difference between the sampling methods. The collection of large "splash" droplets, may also contribute. Future occupational aerosol standards for metalworking fluids will be based on the new, health-related criteria, and exposures will be assessed on the basis of the inhalable fraction. Results of studies like that described here will enable assessment of the impact on future workplace aerosol exposure assessments of introducing new standards.

Keywords: aerosol exposures, metalworking fluids

Much discussion has taken place during the past decade on a particle size-selective, health-based rationale for aerosol exposure assessment, and has led to substantial international agreement by the International Organization for Standardization (ISO),[1] the Comité Européen Normalisation (CEN),[2] and the American Conference of Governmental Industrial Hygienists (ACGIH)[3] on a unified set of particle size-selective sampling criteria. The central theme of these criteria is that aerosol exposure should be assessed in terms of the aerosol fraction, which can reach the target region of the respiratory tract for the health effect in question. In particular, the inhalable fraction—representing particles that are capable of entering the body through the nose and/or mouth during breathing—is considered more appropriate than the "total" aerosol approach, which is the basis of past and current practice in most countries.

Meanwhile, occupational exposure limits for many workplace aerosol exposures have been under consideration for change in light of new toxicologic and epidemiologic information. Metalworking fluid aerosols are one such case. Here, according to the National Institute for Occupational Safety and Health (NIOSH),[4] the number of workers in the United States exposed daily to such aerosols may be of the order of one million, in industries ranging from large machining facilities of the automobile manufacturers to small, specialized metalworking "job" shops.

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A wide variety of metalworking fluids is available, and types are chosen for individual applications on the basis of their ability to provide desired levels of cooling and corrosion protection and permit the desired quality of metal surface finish. These range from straight cutting oils, which can enable very high quality finish, to water-based fluids, which can provide high performance in cooling. For aerosols generated by the use of such fluids, a variety of health effects have been identified, ranging from carcinogenic effects for straight oils (especially those that were not adequately refined) to chronic respiratory effects for both straight oils and aqueous fluids.

At present, ACGIH[3] recommends a threshold limit value (TLV™) only for mineral oil mist (as sampled by a method that does not collect vapor), and this is currently given as 5 mg/m^3 for the fraction described as "total" aerosol. However, ACGIH has declared a "notice of intended change" in which that level is retained only for oils that are described as "severely refined," and that the level will be lowered to 0.2 mg/m^3 for oils that are only "mildly refined." The latter is based on the fact that, due to the presence of polycyclic aromatic hydrocarbons , such oils are "confirmed human carcinogens." Indeed, it has been suggested that exposure to such aerosols may be associated with increased risk of laryngeal cancer.[5] For straight cutting oil, in light of the proposed new particle size-selective sampling criteria, it is appropriate that exposure assessment—and limit values—should be based in the future on the inhalable fraction. There are currently no corresponding ACGIH recommendations for aerosols associated with aqueous metalworking fluids. In general, although the TLVs are not regulatory standards per se, they are influential in the setting of formal standards in many countries.

The work described in this article is part of a large body of workplace exposure assessment research over a wide range of industries, in which it is intended to compare workers' exposures as measured according to the current "total" aerosol rationale with those measured according to the new inhalability criterion. This is based on the fact that a change in rationale must inevitably involve a change in sampling instrumentation. Such work is needed to assess the possible impact of changes on actual measured worker exposure levels, preferably before implementation of the new framework for TLVs.[3] The present study was conducted during the summer of 1994 in a large machining facility that specializes in fabricating high-precision, military-specification metal components, and involved the gravimetric assessment of sampled aerosols generated from straight cutting oils.

METHODS

The Industrial Process

The research was carried out in two machining areas (referred to as Workplace 1 and Workplace 2) located in a single building of a manufacturing facility involved in the production of high-precision metal components. Oil mists were generated from nonaqueous cutting oils used during the automated lathe working of metal rod stock. The rod stock rotated at from 750 to 2500 revolutions per minute, and the cutting oil was applied to lubricate, cool, and protect the metalworking surfaces. Oil mist aerosol was formed by the shearing forces experienced by the resultant liquid film at the rapidly rotating metal surface. The oil itself was a so-called straight oil, a nonaqueous material prepared from petroleum crude. In Workplace 1, the primary oil was Promax 1074 (Ashland Oil Inc.), a solvent-refined light paraffinic distillate; in Workplace 2, the primary oil was Ordnance Oil 300 (Lyondell Petrochemical Co.), a severely hydrotreated heavy naphthenic distillate. In both workplaces each machine was fitted with a centrifugal mist collector designed to capture the oil mist aerosol generated and to discharge the cleaned air back into the factory environment.

Aerosol Exposure Assessment

There were five or six workers in each workplace of interest. Although the selection of workers for sampling was carried out as randomly as possible, the strategy was influenced somewhat by the willingness of workers to participate on any given day. By the end of the study, however, most of the workers had participated, and some had been sampled more than once. For the purpose of aerosol sampling, "total" aerosol is currently understood in North America (and many other countries) to mean use of the closed-face 37-mm plastic filter cassette, as described in the NIOSH *Manual of Analytical Methods, 4th Edition*.[6] In relation to the new sampling criteria, inhalable aerosol is defined quantitatively in terms of a curve describing the aspiration efficiency of the human head (or inhalability) as a function of particle aerodynamic diameter (d_{ae}). For ranges of conditions corresponding to workplaces, and based on wind tunnel experiments with life-size mannequins, this is described by a convention that defines inhalability (I) by the empirical curve[1–3]

$$I = 0.5\ \{1 + \exp\ (-0.06\ d_{ae})\} \quad (1)$$

for d_{ae} up to and including at least 100 µm. The emergence of this criteria has stimulated a search for instrumentation whose performance as a function of particle size matches Equation 1. Recent experiments in wind tunnels with mannequin-mounted personal samplers, as part of a large project funded by the European Commission to identify new sampling instrumentation and methods for their evaluation, have shown that the 37-mm sampler referred to above clearly undersamples with respect to the inhalability curve.[7,8] However, a small number of samplers were identified as providing an acceptable match with the criterion under conditions (i.e., particle sizes, wind speeds) corresponding to those expected in most workplaces. Of these, just one was designed from the outset specifically to collect the inhalable fraction. This is the Institute of Occupational Medicine (IOM) inhalable aerosol sampler (first described by Mark and Vincent[9] and now available commercially from SKC Inc., Eighty Four, Pa.), which operates at a flow rate of 2 L/min and incorporates a 25-mm filter. This filter is incorporated into a small plastic cassette into which sampled air enters through a 15 mm-diameter circular orifice, and it is the whole catch of the cassette (both filter and the internal walls) that represents the inhalable fraction.

Both the IOM and 37-mm samplers were used in the present study, with the objective of determining (a) the level of personal worker exposure obtained by each method (E_{IOM} and E_{37}, respectively), and (b) the comparison E_{IOM} versus E_{37} for each workplace. For each worker participating in the study, one of each type of sampler was worn side-by-side in the lapel region, using a specially designed harness. They were placed on alternate sides from one worker to the next to minimize any bias arising from the "handedness" of the workers. To achieve sampling in this way, each worker also wore two small sampling pumps (Model Aircheck 50, SKC Inc.), which were mounted together inside a belt-mounted cloth pouch (to optimize the comfort of the wearer).

Since the collected samples were to be assessed gravimetrically, the authors chose to use polyvinylchloride filters, which are known to exhibit low tare weight and low moisture adsorption (and hence good mass stability). They also chose filters with 5 µm pore size to minimize pressure drop and yet provide good particle collection in the size range of interest.

It was recognized that aerosol particle size can have a significant bearing on the collection efficiencies of the samplers used. So measurements were made of the particle size distributions of the aerosols, using a cascade impactor-based, 2 L/min personal inhalable dust spectrometer (PIDS) (first described by Gibson et al.[10]). The main feature of this instrument that distinguishes it from other personal cascade impactors used in industrial hygiene investigations is the 15-mm entry, which, similar to the IOM sampler, allows aspiration of the inhalable fraction as defined by Equation 1. Also, all the aerosol that enters the instrument is evaluated and used in the determination of the inhalable aerosol particle size distribution. The authors considered it sufficient to mount the PIDS samplers on life-size mannequins that were placed in the workplace as close as possible to the workers themselves.

Analysis of Samples

For all the samples taken, quantitative analysis involved determination of the mass of overall particulate matter collected. The analyses for the masses of collected particulate matter were conducted on site. For the 37-mm sampler, gravimetric assessment of the collected aerosol involved weighing the filter before and after sampling, with the difference providing the mass of sampled overall aerosol that deposited onto the filter. No account was taken of internal wall deposits. This is the most common mode of use for this sampler. For the IOM personal inhalable aerosol sampler, the whole cassette was weighed—again before and after sampling—so that internal wall losses were explicitly included. For the PIDS, each collection stage of the instrument (i.e., entry, impactor stages, and backup filter) was similarly evaluated. To minimize variability associated with moisture adsorption, all samples were conditioned prior to weighing by placing them in a dessicator overnight. The weighings were performed using an electronic balance (Model RC210P, Sartorius, Goettingen, Germany).

Analysis of Data

The comparison of the data for the two samplers was performed using linear regression techniques aimed at identifying differences between the working groups for given work sites and processes.[11] In particular, the results were analyzed in terms of the relation

$$E_{IOM} = S \bullet E_{37} \quad (2)$$

where E_{IOM} is the exposure to inhalable aerosol obtained using the IOM sampler and E_{37} is the exposure to "total" aerosol obtained using the 37-mm sampler, and where S is a coefficient that describes the observed relationship—assumed to be linear and passing through the origin of coordinates—between the two measures of exposure. For the regression analysis, weighted least squares (WLS) was found to be most appropriate to this study (and others like it) in which all the results were weighted according to the inverse of the variance, expressed as $1/(E_{37})^2$. In Equation 2 it is implicit that the intention is to determine S so that E_{IOM} may be predicted from measurement of E_{37}.

The raw data from the PIDS were analyzed using a new inversion method described by Ramachandran et al.[12]

RESULTS

The results of 23 individual comparisons of worker-paired inhalable and "total" aerosol exposure measurements are presented in Figure 1 in the form of a plot of E_{IOM} versus E_{37}. Here, the two workplaces, considered at the outset to reasonably define two distinct groups, are identified by the symbol used. The results are plotted on log axes to best portray the data over the full ranges of exposure concentrations. On these axes, the fitted relationship appears as a line that is parallel to, but displaced from, the 1:1 line. Therefore, the fitted slope, S, may be read off the graph from the magnitude of the displacement of the fitted line from the 1:1 line. The line drawn on each graph is the one obtained by the WLS regression after the consideration of possible outliers meeting specific technical and statistical criteria.[11]

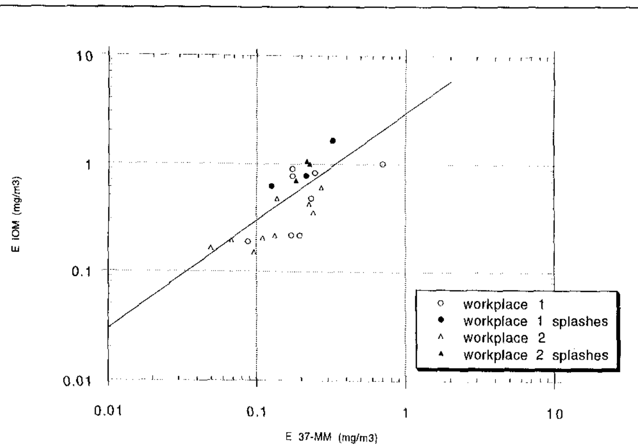

FIGURE 1. Graph showing the comparison between worker exposures to "total" aerosol (as measured using the 37-mm sampler) and inhalable aerosol (as measured using the IOM sampler). Results are shown for two machining areas (Workplace 1 and Workplace 2) characterized by the lathe machining of rod stock of different metals and using different cutting oils. Results for which there was visual evidence of splashing around the inlet of the IOM sampler are identified. The solid line derives from weighted least squares regression of the data, with slope S=2.96±0.60 (standard error) based on Equation 2.

Regarding sample quality, of all the samples collected, only one was rejected outright, and that was because the filter had been splashed with oil to the extent that the flow rate dropped significantly. Several other samples caused some consternation because it was possible to see with the naked eye—under strong illumination—evidence of the impaction of quite large droplets on the inside lips of the IOM cassette. This raised the question about whether the droplets had been truly airborne (and hence would indeed have been inhalable) or whether they had been the result of direct splashing. The experimental points corresponding to these observations are identified in Figure 1. However, confidence in these as real data points was increased when none of them was qualified for removal under the chosen technical and statistical criteria. So all the data shown in Figure 1 were used in the determination of S in Equation 2.

The results show that the exposure based on the inhalable fraction (E_{IOM}) exceeds that based on "total" aerosol (E_{37}) by a factor estimated as close to 3 for both workplaces investigated. In view of the small number of samples taken at each workplace, and the magnitudes of the standard errors, it was not possible to identify significant differences between the two workplaces. So despite the fact that different oils were being used in the two workplaces and that different materials were being turned on the lathes, which were therefore operating at different rates of rotation, justification was seen for combining the two sets of data. When this was done, the overall result from the 23 pairs of samples taken was $S=2.96\pm0.60$ (standard error).

Finally, five sets of data were obtained for the particle size distribution using the PIDS, two in Workplace 1 and three in Workplace 2. Due to the generally low concentrations of the workplace aerosol in both workplaces, the masses collected on some of the PIDS stages were not sufficient to permit accurate determinations of particle size distribution. So detailed results are not given here. However, it was possible to estimate with confidence that the mass median aerodynamic diameter of inhalable particles was between 10 and 15 μm for both workplaces.

Discussion

The main feature of the intersampler comparison results is that the value of S—representing the ratio E_{IOM}/E_{37} as given by Equation 2—is significantly greater than unity. This is consistent with what is known from wind tunnel experiments about the aspiration efficiencies of the two samplers, as well as the fact that, only the filter of the 37-mm sampler was analyzed (so that internal wall losses were not accounted for). It is also supported by what is known of the physics of the sampling process, particularly as it depends on particle size.[13] However, the actual S-value obtained from WLS analysis of the results obtained in this study should be regarded more as indicative than definitive. That is, although results for oil mists elsewhere are expected to be different, the general trend will be the same. From the results of studies conducted in a range of other industries,[14–16] S-values of at least 2 have come to be expected for particles in the sort of size range encountered in the machining facility studied. Taking into account the magnitude of the error, the present results are broadly consistent with that expectation.

The imprecision of the estimate for S (as reflected in the standard error shown) is large enough to preclude a quantitative determination of systematic differences in S between the two work sites for the number of samples obtained. From physical considerations of the aerosol generation process, involving the oil type and lathe rotating speeds, it is not unreasonable to expect differences. But in the complex and highly variable workplace setting, many more samples would be needed to enable experimental identification of such differences.

The IOM sampler has emerged as a candidate sampler matching the new inhalability criterion. Others also look promising.[8] Eventually, when aerosol standards based on this criterion are implemented, it is likely that such sampling instruments will be increasingly deployed. The IOM sampler has been shown to work well, with few problems, in many industrial environments. However, as identified in the present work, there are some technical problems that need to be addressed. The question of the collection of splashing in some situations (e.g., metalworking, electroplating operations, etc.) may undermine confidence that the IOM sampler is truly collecting the inhalable fraction. Elsewhere, there has been anecdotal evidence that related problems may occur in other industries (e.g., woodworking) when large particles may be projected directly into the sampling orifice. The problem in general derives from the fact that the IOM sampler has a relatively large opening that faces outwards. The dilemma is that this is the very feature that enables the aspiration efficiency of the IOM sampler to match the inhalability of humans. However, it is appropriate to look for technical solutions to the problem, including the possibility of incorporating a splash-guard or deflector. Such improvements are being considered.

Conclusions

It has been shown that for the machining areas studied the IOM sampler consistently collects more oil mist aerosol than the 37-mm sampler. That is, inhalable aerosol exposures are systematically higher than what has been regarded as "total" aerosol. This may appear anomalous until it is pointed out that "total" aerosol—as measured using instruments like the 37-mm sampler—is not equivalent to true total aerosol. In fact, from both wind tunnel and workplace evidence, it is now known that the 37-mm sampler undersamples with respect to true total aerosol and inhalable aerosol.

The results of this study follow the trend found in other industries.[14–16] Such findings are important since, in the future, occupational aerosol standards will be based on the new health-related criteria adopted by ACGIH (1995) and other bodies. For straight-oil machining fluids of the type described, this means that exposures will be assessed on the basis of the inhalable fraction. The results of studies like that described here therefore provide, in the first instance, means by which current "total" aerosol exposure values may be converted to new inhalable ones. Further, they enable an assessment to be made of the impact of introducing such new standards—by, for example, examining the rate (or probability) of finding measured exposures above the limit value. Inevitably, that rate will increase with the implementation of the inhalability criterion—unless, of course, the limit value is also raised (an option that may, or may not, be appropriate, depending on the original basis of the limit value).[17] Although for the machining facility in question exposures were generally low in relation to the current limit value for mineral oil mists (5 mg/m^3), the problem will become more significant if and when new, lower, limit values are introduced. Results like those described in this article will therefore be important in future discussions about policies for occupational health standards.

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