PAPER

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Comparison of wood-dust aerosol size-distributions collected by air samplers

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Received 14th October 2003, Accepted 18th November 2003
First published as an Advance Article on the web 5th December 2003

A method has been described previously for determining particle size distributions in the inhalable size range collected by personal samplers for wood dust. In this method, the particles collected by a sampler are removed, suspended, and re-deposited on a mixed cellulose-ester filter, and examined by optical microscopy to determine particle aerodynamic diameters. This method is particularly appropriate to wood-dust particles which are generally large and close to rectangular prisms in shape. The method was used to investigate the differences in total mass found previously in studies of side-by-side sample collection with different sampler types. Over 200 wood-dust samples were collected in three different wood-products industries, using the traditional 37 mm closed-face polystyrene/acrylonitrile cassette (CFC), the Institute of Occupational Medicine (IOM) inhalable sampler, and the Button sampler developed by the University of Cincinnati. Total mass concentration results from the samplers were found to be in approximately the same ratio as those from traditional long-term gravimetric samples, but about an order of magnitude higher. Investigation of the size distributions revealed several differences between the samplers. The wood dust particulate mass appears to be concentrated in the range 10–70 aerodynamic equivalent diameter (AED), but with a substantial mass contribution from particles larger than 100 μm AED in a significant number of samples. These ultra-large particles were found in 65% of the IOM samples, 42% of the CFC samples and 32% of the Button samples. Where present, particles of this size range dominated the total mass collected, contributing an average 53% (range 10–95%). However, significant differences were still found after removal of the ultra-large particles. In general, the IOM and CFC samplers appeared to operate in accordance with previous laboratory studies, such that they both collected similar quantities of particles at the smaller diameters, up to about 30–40 μm AED, after which the CFC collection efficiency was reduced dramatically compared to the IOM. The Button sampler collected significantly less than the IOM at particle sizes between 10.1 and 50 μm AED. The collection efficiency of the Button sampler was significantly different from that of the CFC for particle sizes between 10.1 and 40 μm AED, and the total mass concentration given by the Button sampler was significantly less than that given by the CFC, even in the absence of ultra-large particles. The results are consistent with some relevant laboratory studies.

Introduction

The significance of the health impact of exposure to airborne wood dust has been described in the previous publications relating to this work.[1,2] The projected goal of this research is to assess the impact of recent proposed changes in evaluating worker's exposure to wood dust as documented in the Notice of Intended Change in the American Conference of Governmental Industrial Hygienists Threshold Limit Values (ACGIH®-TLV®).[3] The Notice of Intended Change includes a change in both the numerical limit values and in the method of sample collection to be in accordance with the "inhalable" convention. The inhalable convention is defined as the probability of particle collection by the nose and mouth for particle sizes up to 100 μm aerodynamic equivalent diameter (AED).[4] The largest of these particles, *i.e.* those between 10 μm and 100 μm AED, are most likely to be deposited in the upper airways, including the nasal passages. The TLV is set to protect against sino-nasal cancer and other upper airways diseases such as asthma and chronic bronchitis,[5–7] in which case the inhalable dust fraction is the most appropriate for assessing health-based exposure risks in wood-working industries. Samplers which operate in accordance with this convention are known to collect significantly more large particles (> 10 μm AED) than the current "total" dust 37 mm styrene/acrylonitrile closed-face cassette (CFC) sampler, which is the basis of most US standards and regulations, but which is not considered the best available inhalable sampler based on laboratory tests.[8] Although large particles normally settle rapidly, they can remain airborne over significant distances if projected from cutting or grinding tools with sufficient velocity, and if there is an entrained air-flow in the direction of projection. Large projectile particles are relatively common in the wood-working industries,[9] and it is possible that the aerodynamic properties of thin, flat, plate-like particles ("frisbees"), may contribute to keeping these particles airborne against their natural tendency to fall under the influence of gravity. For most coarse dusts a

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DOI: 10.1039/b312883k

correction factor of 2.5× has been suggested for converting "total" dust (CFC) samples to the corresponding inhalable value.[10] In the case of exposures to wood dust, several studies with side-by-side sampling have revealed that inhalable sampling will increase the apparent dustiness of an atmosphere by between 150 and 400%, with an average closer to the higher end of this range.[2,11–15] However, this data may be confounded by the ability of most commercially available inhalable samplers also to collect very large (ultra-large) particles (>100 μm AED) which are beyond the range of the inhalable convention.[16] The large mass associated with these large particles can cause a serious bias in the comparisons. Experiments on ultra-large particles[17,18] have shown them to have a much smaller probability for inhalation, so that it may be appropriate to exclude them from a health-based standard. However, there have been no studies on the impact of such particles on the mass collected by personal samplers in field situations, as there has been no method by which this could be done.

The present study began as a Pilot Project with a proposal to examine the sampling characteristics of three samplers under field use conditions in the wood-working industries. The three samplers selected were the aforementioned closed-face, 37 mm cassette (CFC) as used in the NIOSH Method 0500 for Particles Not Otherwise Classified (often colloquially referred to as "Total Dust"),[19,20] the Institute of Occupational Medicine (IOM) sampler,[21,22] and the Button sampler developed by the University of Cincinnati.[23,24] The study design included the collection of side-by-side samples using the CFC, IOM, and the Button sampler, in all combinations.

Research design and methods

The sampling sites and procedures have been described previously.[1] It is important to keep in mind that, in order to comply with restrictions on the analytical methodology, samples in this study were taken for periods from ten minutes up to two hours, so that insufficient dust was collected to allow for gravimetric analysis. Particle masses, and hence concentrations, were determined from particle size measurements and known densities, corrected for blanks. An estimated twenty to thirty thousand measurements were made of individual particles from approximately two hundred samples using phase-contrast microscopy. The quality assurance of the procedure was investigated on a small number of samples before proceeding with the full sample set, and the results have been published, and suggest an accuracy similar to that of other microscopic methods, such as fiber-counting.[1] Particles were sized in the *x*- and *y*-dimensions, and the *z*-dimension was calculated using an algorithm based on the analysis of more than one thousand particles by laser confocal microscopy. The test particles were drawn from multiple samples of different wood types and exposure situations, and the equation that best matched the data has been published previously.[1] Aerodynamic equivalent diameters were calculated from equations of Lee and Leith and Johnson *et al.*,[25,26] as described previously,[1] whose utility had been verified through analysis of many differently-shaped particles, including plate-like particles similar in shape to wood-dust. The particle aerodynamic equivalent diameters (AED) were converted to particle masses found in size-range classes (<10 μm, 10.1–20 μm, ..., 90.1–100 μm, >100 μm), and for each size range class a concentration was calculated from the mass of particles and the known air sample volume.

Statistical analysis was carried out to compare the concentrations found in the different size ranges from the three samplers. Certain factors, such as wood type and job description (sander or non-sander), and also total and size-reduced concentrations are correlated, since the three factories studied used different woods, and performed different operations, and had different approaches to dust control. The samplers, however, had been deployed in mixed pairs, so that it was possible to do a pair-wise comparison using paired *t* statistics separately for each sampler pairing. This design also lends itself to mixed model analysis of variance since it can be thought of as an incomplete block design with individual subjects as blocks.[27] Every possible pair of samplers does not appear in every subject but every pair does appear more than once and also appears nearly the same number of times over the whole sample. SAS PROC MIXED[28] was used for this analysis because it can handle incomplete unbalanced designs of this sort. One advantage of using the mixed model analysis is that it makes use of all of the information in the sample using one global estimation model where the paired comparisons do not. This can lead to a more powerful analysis because of increased degrees of freedom for estimating standard errors. After qualitatively comparing the results of the pair-wise comparison with those from the mixed-model analysis, where factors such as wood type and job description were accounted for as covariates, it was noted that the analysis approach and the factors listed above did not affect the basic patterns of differences in the sampler comparisons, and so the results given below are based on the mixed-model analysis. The multiple comparisons across sampler pairs and diameter size ranges presented in the results (Table 2) were adjusted for multiple testing across the three sample pairs using the Scheffe's test (*e.g.* the *p* values listed in the table are adjusted for three pair-wise comparisons) and are then considered significant for $p < 0.0045$ ($\alpha = 0.05/11$) to account for multiple comparisons over the eleven size classes.

Results and discussion

Ultra-large particles have the potential to make up a very significant portion of the total sample load on a mass basis, even though their numbers are small. When present on the samples collected in this study, that is 65% of the IOM samples, 42% of the CFC samples and 32% of the Button samples, ultra-large particles accounted for 53% on average (range 10–95%) of the total mass collected, regardless of sampler type. Their control on the total mass collected is illustrated graphically in Fig. 1(a–c), where the relationship between the total mass concentration and the mass concentration of only particles >100 μm AED is shown in the graphs. The correlation coefficients are 0.919 (IOM), 0.939 (CFC) and 0.897 (Button). The spread of the total mass concentration results from samplers that did not collect particles >100 μm AED is provided on the left for comparison purposes. Differences in the collection efficiency for the ultra-large particles accounted for some, but by no means all, of the differences between the samplers. The geometric mean concentrations found for the three samplers, with and without the ultra-large particles, and for the ultra-large particles alone, are given in Table 1. When compared to long-term gravimetric sample results, such as those collected previously,[2] concentration values are higher using the microscopic method. A bias in that direction is to be expected, since there are periods in a full work-shift where dust is not being generated. In general, the difference between the two studies appears to be around an order of magnitude, both for individual work-sites (for example, the geometric mean of CFC samples from the furniture shop was 7.1 mg m^{-3} for long-term gravimetric samples and 93 mg m^{-3} for short-term microscopic samples, while the corresponding values for the shutter-blind establishment were 2.0 mg m^{-3} and 22 mg m^{-3}), and across the entire studies (gravimetric study, all CFC's, geometric mean = 2.5 mg m^{-3}; this study, all CFC's, geometric mean = 22 mg m^{-3}). While an order of magnitude difference between short and long-term results is within the realm of

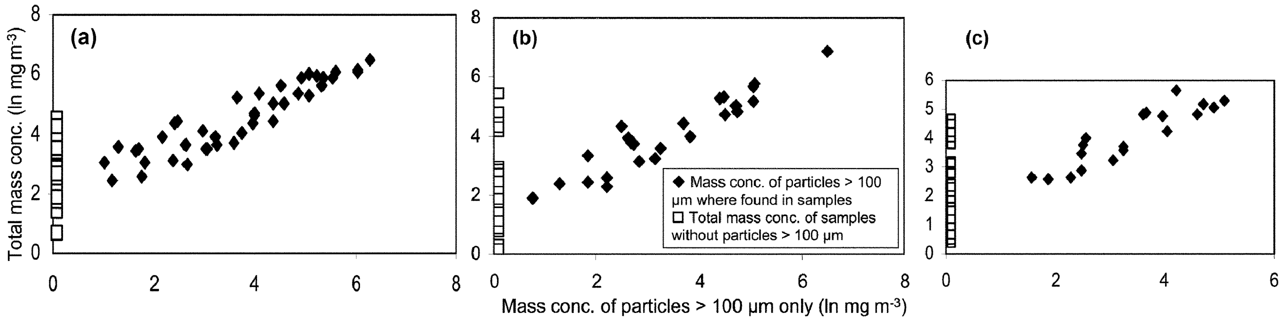

Fig. 1 The effect of particles >100 µm AED on total mass collected. The range of total mass concentrations for samplers without ultra-large particles is shown at left. For samples containing ultra-large particles, the domination of the total sample mass by these particles is shown on the right by the strong correlation between total mass concentration and ultra-large particle mass concentration. (a) IOM, (b) Button, (c) CFC.

Table 1 Comparison of sampler means for all samples, samples not containing ultra-large particles, and samples containing ultra-large particles. Note that these values are about a factor of ten higher than normal workplace measurements

	All samplers		Samplers with particles <100 µm AED only		Samplers with particles >100 µm AED	
	n	Geometric mean/ mg m^{-3}	*n*	Geometric mean/ mg m^{-3}	*n*	Geometric mean/ mg m^{-3}
IOM	65	48.0	23	14.1	42	94.0
CFC	62	22.2	36	11.8	26	53.1
Button	59	14.0	40	7.1	19	58.3

possibility, it is certainly possible that these differences may also reflect a bias in the microscopic technique, since it has not yet been possible to calibrate the microscopic technique against known dust masses. Therefore, the results provided here should be used only for the purposes of comparison between samplers and not as an indication of the hazard potential of the workplaces. Based on the results in Table 1, the IOM collects about 2.16 times more dust than the CFC, which is less than the ratio of 3.35 found in our previous study of long-term gravimetric sampling.[2] This may be due to the inclusion of particles found on the walls of the CFC which were not included in the gravimetric study. Once the effect of particles >100 µm AED is removed, the ratio falls to 1.86, but not to 1.0. The ratio between the IOM and Button is 3.43, which is close to the 3.14 found in our previous study. Again, removal of the ultra-large particles reduces the ratio, to 2.62, but not to unity. The ratio between the CFC and Button is 1.59, fairly close to the 1.2 found previously, which reduces to 1.41 on removal of the ultra-large particles.

Using mixed model comparisons for the means listed in Table 1 leads to the conclusion that for samples with particles greater than 100 µm AED, the Button *versus* IOM and CFC *versus* IOM are not quite significant ($p = 0.1781$ and $p = 0.1241$ respectively after adjustment for three multiple comparisons) while the Button *versus* CFC contrast is not significant at all ($p = 0.999$). For samples without particles 100 µm AED or larger the Button *versus* CFC contrast is significant ($p = 0.04$), and the Button *versus* IOM difference is significant ($p = 0.005$), while the CFC *versus* IOM contrast is not significant ($p = 0.5$).

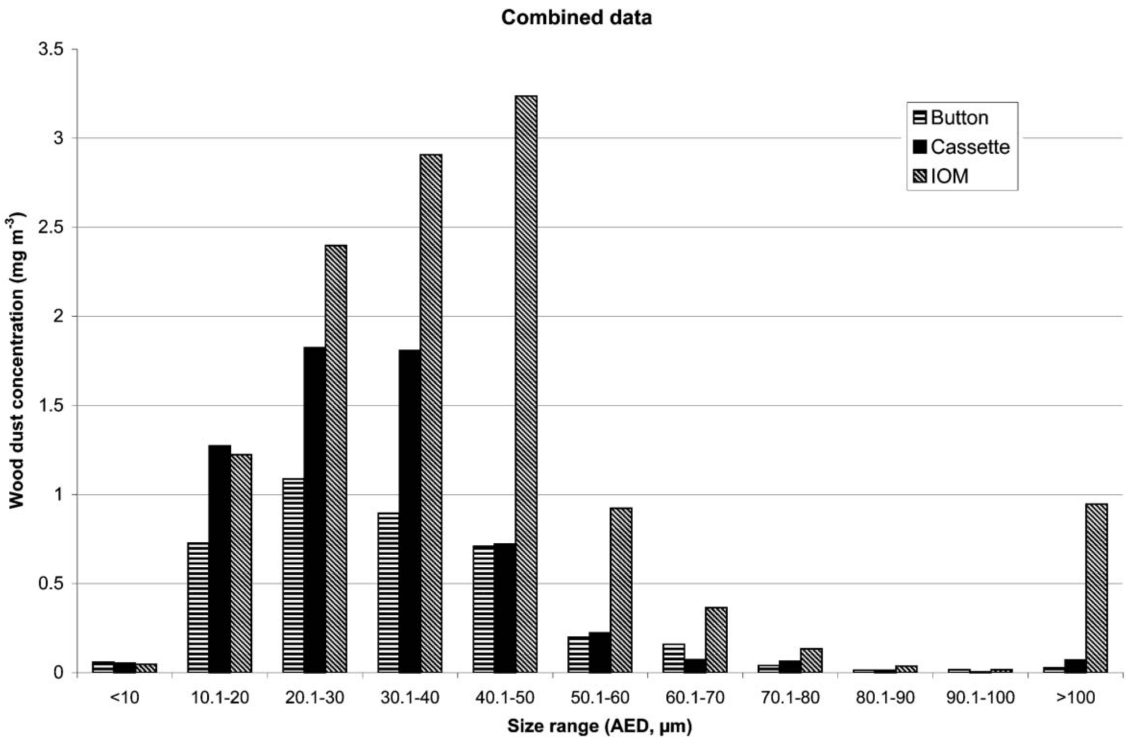

Fig. 2 Comparison of wood dust particle sizes collected by samplers, expressed as geometric mean mass concentration in air for each size-range.

Table 2 *p* values for size-range comparisons from mixed model

Sampler comparison	Aerodynamic equivalent diameter size-range/µm <10	10.1–20	20.1–30	30.1–40	40.1–50	50.1–60	60.1–70	70.1–80	80.1–90	90.1–100	>100
Button/CFC	0.9877	<.0001[a]	<.0001[a]	0.0002[a]	1.0000	0.7779	0.5168	0.7774	0.9972	0.0504	0.6200
Button/IOM	0.9965	<.0001[a]	<.0001[a]	<.0001[a]	0.0024[a]	0.0184	0.6757	0.2889	0.3702	0.8671	0.0008[a]
CFC/IOM	0.9970	0.7313	0.0397	0.1509	0.0020[a]	0.0933	0.1185	0.6805	0.3987	0.1348	0.0147

[a] Significant difference ($p > 0.0045$)

When the other size ranges are considered, the reason for the remaining differences becomes clear. The geometric mean concentrations collected in the different size ranges are shown in Fig. 2. The significance of the differences is given in Table 2. Using the Bonferroni correction, the significant cut-off is $p = 0.0045$. In the size range below 10 µm AED, there is no significant difference between the samplers, but this is not very important as very little mass is collected in this range. In the range 10.1–20 µm AED, there is no significant difference between the IOM and CFC samplers, in line with laboratory experimental data.[8] In the ranges 20.1–30, 30.1–40 and 40.1–50 µm AED, a progressively greater difference between the IOM and CFC is observed, although because of the large geometric standard deviations, the difference is only significant for the 40.1–50 µm AED range. Both the IOM sampler and the CFC collect progressively less mass in the size ranges above 50 µm AED, presumably reflecting a real drop in particle concentration at the tail of the mean airborne size distribution. The IOM still appears to collect more than the CFC, although the significance of the difference is lost, presumably because of the large standard deviations observed with the low numbers of data points (many samples did not contain particles in these size ranges). The Button sampler is significantly different from the IOM, collecting less material in all size ranges between 10.1 and 60 µm AED, and this finding is counter to some laboratory studies.[23] The Button is also significantly different (lower) with respect to the CFC in the ranges between 10.1 and 40 µm AED ranges. This does not appear to be in accord with the results of the 30 µm test aerosol data reported by Aizenberg *et al.*,[29] but it is compatible with the data presented by Li *et al.* for the Button sampler in the 90° orientation.[30] Note that particles adhering to the inner walls of the CFC were included in the analysis for the present study, thereby capturing much of the loss seen for the same size range with the CFC in Li *et al.*'s work. It is interesting to note that the porous shield tested on the IOM sampler as a defense against collecting ultra-large particles also was found to have reduced collection efficiency for the smaller particle sizes in a previous study.[17] It may be possible that this reduced efficiency is related to particle impaction and bounce on the surface of the screen.

When comparing the size distributions of dust in samplers that have collected ultra-large particles with those that have not, it is strikingly apparent that the former contain more dust in the size-ranges below 100 µm AED in addition to the ultra-large particles. For the IOM and Button samplers that have collected ultra-large particles, the total mass concentration in the <100 µm AED size region is about three times greater than that seen in samplers that did not collect ultra-large particles. Part of this increase is a general increase in concentration across all size ranges above 10 µm AED, but part is due to a greater increase in the concentration of particles above 50 µm AED. For the CFC the difference between concentrations of particles <100 µm AED where particles >100 µm AED are present and where they are not is a factor of two, reflecting the poorer collection efficiency of the CFC for particles above 50 µm AED.

Where a limit value has been set using epidemiological data based on exposure measurements made with a specific sampler, which is the case for wood dust and the CFC, the large number of exposure measurements has allowed a relationship between wood-dust concentration and health effects to be established, but the relationship has likely been skewed by the effect of ultra-large particles (although the relationship still exists because of the increased concentration of smaller particles where ultra-large particles are present). If the same sampler is used to characterize another workplace where processes are similar, the presence of ultra-large particles in both the data-set used to set a limit value, and in the workplace being characterized, would tend to cancel out. However, even in this ideal case, such a comparison would only be true for the average of a large number of samples, and it would not be possible to ascertain whether any single sample was above the limit value because of excessive dust in the size-range of concern, or because of the presence of ultra-large particles. Using a different sampler to demonstrate compliance with a limit value becomes even more problematic. Since the different sampler types collect different size-ranges of particles (including the ultra-large) with different efficiencies, a conversion factor must be applied to compare the results. Side-by-side comparisons have been done a number of times for the CFC and the IOM, and the average conversion factor has now been well-established at an IOM/CFC ratio of around 2–4. However, again, this ratio cannot be applied to individual results. Since an IOM sample is much more likely (approximately 50% more likely) than a CFC sample to contain ultra-large particles, any individual IOM result has a greater chance of exceeding a limit value (even when corrected for the average difference between the two sampler types) than any CFC sample. For example, even though the median difference between the pairs of the two samplers in this study was 2.32, individual samplers could differ by a factor of 30. Such a large difference would almost certainly have caused the IOM sample to be over the limit value (even a corrected value), even where the CFC sample was not. It may be necessary to deal with populations of results, rather than an individual workers' result when evaluating results from different samplers. For example, if large numbers of IOM results are available from a single workplace, then the study reported here suggests that 65% of those samples would contain ultra-large particles, and that those samples would show a mass concentration raised above the other 35% of samples by a factor of approximately 3, by virtue of containing more particles in the 10–100 µm AED size range, and a further factor of approximately 2.2 through the presence of the ultra-large particles.

One possible way of dealing with the situation where there are only a few measurements is to identify those samplers containing ultra-large particles by visual observation. Although an observer with acute eyesight can see individual objects down to around 50 µm, a more realistic cut-off is 100 µm (0.1 mm). In general, wood dust particles greater than 100 µm AED are often much larger than 100 µm in their greatest diameter. In the past, it has been suggested that visually-recognizable individual particles should be picked out from the sample by hand, a process likely to disturb the rest of the sample. Instead, it may be possible to derive a mathematical solution to correct for their presence along the lines mentioned above.

Conclusions

Airborne ultra-large particles are relatively common in woodworking environments, probably because of the special aerodynamic qualities of flat, plate-like particles spun into the air ("frisbees"). These large particles can enter the openings of samplers through inertial penetration or gravitational settling. Collection of these particles can be minimized by reducing the size of the sampler orifice (as with the CFC compared to the IOM) or by using a screen of small orifices (as with the Button), but probably cannot be avoided entirely in the samplers available today. Where ultra-large particles are present, their mass strongly dominates the total mass collected, even though collection of ultra-large particles is associated with an increased concentration of smaller particles. If the ultra-large particles are considered not to be associated with adverse health effects, because of their low probability for inhalation, then exposure measurements may not accurately reflect health risks. Adjusting individual sampler results to compare with a limit value adjusted for an average difference between sampler collection efficiency is problematic when the sampler types differ markedly in their collection efficiency for ultra-large particles. The under-sampling of the Button sampler compared to the CFC at size-ranges below 50 µm AED, is also a matter of concern in estimating the true inhalable exposure although this sampler has the lowest collection efficiency for particles greater than 100 µm AED.

Acknowledgements

This sampling and quality assurance phases of this study were initially supported by a NIOSH Pilot Project Research Training Award administered through the Deep South Education and Research Center. Further support for sample analysis through a research gift from Omega Specialty Instruments was greatly appreciated. Final data analysis was completed at NIOSH. This work would not have been possible without the assistance of the UAB Imaging Center, and, in particular, Albert Tousson (the singing microscopist).

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