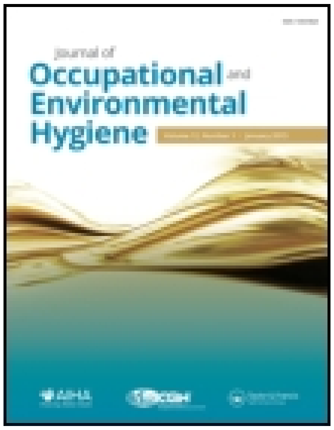

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The current method for sampling aerosols using the 37-mm closed-face cassette (CFC) sampler is based on the orientation of the cassette at ∼45° from horizontal. There is some concern as to whether this method is appropriate and may be underestimating exposures. An alternative orientation at ∼0° (horizontal) has been discussed. This research compared the CFC's orientation at 45° from horizontal to the proposed orientation at horizontal, 0° in a controlled laboratory setting. The particles used in this study were fused alumina oxide in four sizes, approximately 9.5 μm, 12.8 μm, 18 μm, and 44.3 μm in aerodynamic diameter. For each test, one aerosol was dispersed in a wind tunnel operating at 0.2 m/s with samplers mounted in the breathing zone of a rotating mannequin. A sampling event consisted of four pairs of samplers, placed side by side (one pair at 45° and another at 0° cassette orientation), and exposed for a period of 45 minutes. A total of 12 sampling events, 3 sample events per particle size, were conducted with a total of 94 samples collected. Mass concentration measurements were compared to assess the relationship between the sampler orientations of the cassettes. In addition, the relationship between the mass collected on the cassette filter and on the interior walls of the cassette was also assessed. The results indicated that there was no significant difference between the measured concentrations based on the orientation of the CFCs. The amount of mass collected on the interior walls of the cassettes was relatively low (<5%) compared to expected (up to 100%) wall losses for both orientations.

Keywords aerosol, closed-face cassette, particles, sampler orientation, wind tunnel

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INTRODUCTION

Inhalation of dust is an important occupational exposure concern, and potential health effects from inhaling aerosols have been well recognized in the workplace. Accurate measurement of this is important because inhaling high concentrations of dust could result in an undesirable challenge to the body's defense mechanisms.(1) Previously observed adverse health effects that can occur after inhalation of particulates from various sources include asthma, chronic bronchitis, emphysema, and chronic obstructive pulmonary disease (COPD).(2)

Recent research on particle sizes most responsible for observed adverse health effects has led to the adoption of health-based particle size fraction definitions relevant to different areas in the human respiratory tract.(3) The aerosol size ranges of interest include health-related inhalable, thoracic, and respirable particulates.(4–6) These aerosols are commonly found in workplace environments, and may be hazardous when inhaled into the respiratory track.(4) To assure emission controls are working and that exposure levels are maintained at acceptable concentrations, personal sampling methods need to provide an accurate representation of human or possible human exposure to these potentially hazardous aerosols.

Personal samplers, such as the 37-mm closed-face cassette (CFC), are commonly used to measure exposure to "total" aerosols in the workplace. However, the CFC has been associated with low sampling efficiency for particles with diameters >30 μm, which are still considered inhalable. Therefore, the CFC sampler does not match the definition of an inhalable sampler.(7) Several other limitations, including inner wall losses, bypass leakage, non-uniform deposition on collection filter, and under-sampling mass concentrations, have been observed when the inlet orifice is oriented downward at 45°.(8) The CFC sampling efficiency has been shown to decrease not only with increasing particle size but also for large angles away from the direction of airflow. The mean sampling efficiency has been shown to increase for particle sizes 2.4 μm (27%), 9 μm

(21%), and 24 μm (30%) when the orientation was changed from 90° relative to horizontal (facing downwards) to 45° downward from horizontal.[9] This 45° downward alignment is the typical way in which the CFC is used in the field. Therefore, the CFC orientation may be one modifiable factor that is influential in how airborne particles are drawn into this aerosol sampling device. It is hypothesized that there could be a statistical difference between measured concentrations when the orientations of the cassettes are set at 45° from horizontal and horizontal, 0°. If so, then utilizing the CFC at a 0° (horizontal) orientation might provide more accurate exposure data for aerosols in workplace air.

In addition, it has been found that most wind speeds experienced by workers are <0.3 m/s.[10] However, the effect of orientation on the CFC sampler has only been investigated in wind speeds of 1.0 m/s.[9] Therefore, in this study the effect of orientation will be assessed in a lower wind speed environment more representative of what workers are likely to experience.

METHODS

Comparisons of aerosol concentrations collected by two personal samplers at different orientations (45° down from horizontal and horizontal, 0°) were conducted in a wind tunnel at 0.2 m/s. Four different aerosols sizes (approximately 9.5 μm, 12.8 μm, 18 μm, and 44.3 μm in aerodynamic diameter) were used in separate sampling events. The particles were narrowly graded powders of fused alumina oxide (Duralum, Washington Mills, Niagara Falls, NY) that have been extensively tested and used for controlled sampler performance tests.[7,11,12] Three separate sample events per aerosol size were conducted with six or eight samplers per event. A total of 12 sampling events were conducted with a total of 94 valid samples collected.

Following the US National Institute of Occupational Safety and Health (NIOSH) Method 0500, "Particles not Otherwise Regulated," [13] a 37-mm CFC consisting of three polypropylene stages was prepared in a laboratory by assembling the cassette. A 37-mm glass fiber filter (1 μm pore size) was pre-weighed using a microbalance (Model number C-35, ATI CAHN, Boston, MA) before cassette assembly. After weighing, the filter was placed on top of a supporting pad and fitted inside the cassette. In the CFC configuration, the front part contains a 4-mm diameter sampling orifice that is raised ~2 mm from the flat face of the sampler. The back part has a nipple that enables connection to the tube that leads to the pump. The third part was inserted between the two parts to ensure retention of the filter.[14] One field blank was collected per sampling event. Each cassette was assembled, plugged, and placed in a desiccator overnight for a time period of no less than 12 hours to control for moisture uptake.

The low-speed wind tunnel (described fully in Schmees et al. [12]) operated at 0.2 m/s. An air compressor was used in conjunction with a dry dust generator (SAG 410, Topas Gmbh, Dresden, Germany) to inject aerosols into the system. The material was then dispersed into the wind tunnel through the aerosol dispersion system. This is a dual tracking system with an injection nozzle mounted on a motor allowing the nozzle to move vertically in a reciprocating motion. The motor in turn was mounted on an overhead tracking system that conveyed it laterally backwards and forwards.[12] The samplers were mounted on a mannequin continuously rotated reciprocally through a full 360° at two rotations per minute and then back again for the duration of the sample event.

Personal sampling pumps were pre-calibrated to operate at 2 L/min using a Bios DryCal primary flow calibrator (Mesa Labs, Butler, NJ). Each cassette was then attached to its own personal sampling pump. The personal sampling pumps were attached to two belts draped around the mannequin for convenience and space constraints. Four sample cassettes were attached to each shoulder (right and left) of the mannequin with the two sample cassette orientations set at 45° from horizontal on each shoulder, as well as two cassette orientations set at 0° (horizontal) on each shoulder (see Figure 1). All samplers were started and operated concurrently.

Each sampling event lasted 45 minutes. During the sampling event, the field blank was opened outside the wind tunnel and immediately closed. After the sampling event, the sample cassettes were removed from the pumps and plugged immediately. Pump flow rates were then measured again to ensure they had not changed by more than 5%. The samples were then left overnight (12+ hr) in a desiccator. Removal of the filter was done gently using forceps to avoid potential loss of dust due to mishandling. Each filter, including field blanks, was post-weighed and recorded using the same equipment and procedures as used for pre-weighing filters.

As noted earlier, the CFC sampler suffers from interior wall losses and there is no standard method for collection, although collecting the interior wall deposits is carried out by the Occupational Safety and Health Administration (OSHA). It has been suggested that the best approach is wiping the internal surfaces of the cassette with a filter and including any residual material along with the sample filter for analysis.[15] To account for these potential losses, a 25-mm glass fiber filter was pre-weighed and used to wipe the interior walls to collect the deposits. The filter was then post-weighed and the mass gained on the wipe was added to the mass on the filter. Mass per volume concentrations for each sample was calculated by dividing sampled mass (filter plus wipe) by the volume of air sampled (m^3).

SAS 9.3 (SAS Institute, Cary, NC) was used for statistical analysis. A Wilcoxon rank-sum test was performed to assess the relationship of the measured concentrations based on the sample orientations of the cassettes, 45° from horizontal and horizontal 0°, for each particle size. This test was also used to compare the relationship between the mass collected on the cassette filter and on the interior walls. The Wilcoxon rank-sum test was performed because (a) the number of observations was small, (b) the two sample groups were assumed to be independent of each other, and (c) both sample groups were assumed to have approximately similar distributions. The Wilcoxon rank-sum test is a nonparametric alternative to the two sample t-test based on the order in which the observations from the two samples fall. Student t-tests were also used to analyze the mean difference in concentration at the different orientations. Linear regression was used to calculate the best fit estimate of collected particle mass concentration between cassette orientations.

RESULTS

Table I shows the collected mass concentration by particle size, including the percent of the sample collected on the interior walls for each orientation, separated by particle size. An average ratio of the concentration measured at orientations 45° (denominator) vs. 0° (numerator) was calculated for each particle size. For the particle size 9.5 μm the average ratio was 0.99, which indicates there is little difference in concentration between orientations. All other particle sizes show a ratio >1: 12.8 μm (1.15), 18 μm (1.14), and 44.3 μm (1.09), which indicates that there is a slightly larger difference between orientations. However, the Wilcoxon rank-sum test indicated that there was no significant difference (at $\alpha = 0.05$) based on the orientations of the cassettes, 45° from horizontal and horizontal 0°, for any of the four particle sizes: 9.5 μm (P-value = 0.7125), 12.8 μm (P-value = 0.3186), 18 μm (P-value = 0.3000), and 44.3 μm (P-value = 0.6297). Analysis of the mean difference in concentration at the different orientations also did not indicate any significant difference for any of the four particle sizes.

The results of the mass concentrations for all side-by-side cassette orientations at 45° from horizontal and horizontal 0° are depicted in regression lines shown in Figure 2. The graph represents all data separated out into each particle size (9.5 μm, 12.8 μm, 18 μm, and 44.3 μm). Each data point represents the mass concentration for cassettes at 45° from horizontal and horizontal 0° paired next to each other on the mannequin during the same sample event. A regression analysis was performed and the results indicate that the regression lines for particle sizes 9.5 μm ($R^2 = 0.75$, P-value < 0.01) and 12.8 μm ($R^2 = 0.61$, P-value < 0.01) each have a positive slope (0.42 and 0.88, respectively). Particle size 18 μm also indicates a positive slope (0.82), although it is not statistically significant ($R^2 = 0.30$, P-value = 0.08). Particle size 44.3 μm has a slope value near zero (-0.01) (i.e., horizontal) ($R^2 < 0.01$, P-value = 0.96), most likely due to this particle size not having a wide enough concentration range to provide meaningful data for the regression line.

Figure 3 shows the results of the percent of mass collected on the cassette filter and the interior wall of the CFC. The graph represents the average percent of the particulate collected on the cassette filter and the interior wall for all cassettes at each orientation for each particle size. For orientations of cassettes at horizontal 0°, particle sizes 9.5 μm and 12.8 μm, the percent of particles collected on the interior walls were $<2\%$. For particle sizes 18 μm and 44.3 μm, the percent of particles collected on the interior walls was between 2% and 5%. For the orientation of the cassettes at 45° from horizontal, the highest percentage of particle collected on the interior walls was for particle size 12.8 μm at 4.84%. For all other particle sizes, 9.5 μm, 18 μm, and 44.3 μm, the percent collected on the interior walls was $<4\%$ at that orientation. The Wilcoxon rank-sum test indicated that there was no significant difference in the percent of the mass that was collected on interior wall versus on the cassette filter for any of the particle sizes 9.5 μm, 12.8 μm, 18 μm, and 44.3 μm each.

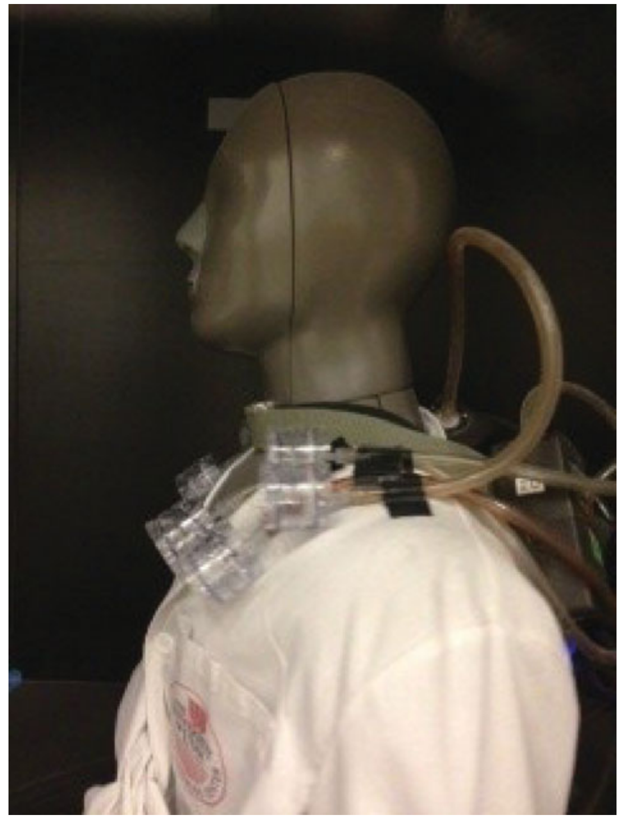

FIGURE 1. Mannequin with cassette orientations at 45° from horizontal and 0°, horizontal

DISCUSSION

The primary purpose of this study was to assess the concentrations collected by the CFC cassettes at orientations 45° downward from horizontal and horizontal, 0°, at a wind speed most common to many workplace environments. The results between orientations 45° from horizontal and horizontal 0° for all particle sizes were not statistically significantly different. In addition, these results show that inclusion of the cassette interior wall deposits has the potential to increase the measured concentration of particles, but only up to ~5%.

It is important to note that these results do not completely reflect the results of other researchers. One study has shown that the efficiency of the CFC cassette can increase in sampling efficiency for particle sizes 2.4 μm (27%), 9 μm (21%), and 24 μm (30%) by using a 45° downward from horizontal orientation vs. a 90° downward orientation, due to the effects

TABLE I. Mean mass concentrations and mean percent of sample collected on the interior wall for orientations at 45° from horizontal and 0°, horizontal, for four particle sizes

		Cassette Orientation				
		45° from Horizontal		0° Horizontal		
Particle Size (μm)	No. of Samples (n)	Mean Concentration (mg/m^3) [SD]	Mean% Mass on Wall [SD]	Mean Concentration (mg/m^3) [SD]	Mean% Mass on Wall [SD]	Ratio (0° : 45°)
9.5	12	48.56 [6.42]	1.44 [1.31]	48.16 [13.29]	1.53 [1.86]	0.99
12.8	12	50.35 [21.93]	4.84 [10.96]	57.81 [19.55]	1.58 [1.77]	1.15
18	11	55.21 [18.18]	1.65 [1.48]	62.69 [12.14]	2.90 [3.02]	1.14
44.3	12	21.10 [3.40]	3.33 [2.20]	23.06 [4.85]	4.16 [4.54]	1.09

of better alignment to the airflow.[9] However, there are major differences about that study. First, that study was conducted without the use of a rotating mannequin, and so the cassettes were pointed directly into the flow of air for the duration of the experiment. Second, the orientations of the cassettes were 45° downward from horizontal orientation vs. 90° downward.

The average of the sample that was collected on the interior walls, based on the filter wipe, was 2.54% for the cassettes oriented at horizontal 0° and 2.82% for the cassettes oriented at 45° from horizontal. These results for the percent of sample collected on the interior walls are not necessarily typical, according to other studies. Wall deposits can often be a large and inconsistent fraction of the total sample; in some instances the entire sample will be deposited on the interior walls.[15]

There may be some explanation as to why this study did not find a difference in cassette orientation. First, this may be because, with the mannequin in constant motion, the orientation of the cassette has the potential to fluctuate. Although this fluctuation was not observed during sampling, it may have restricted the inlet of the sampling cassette and therefore could

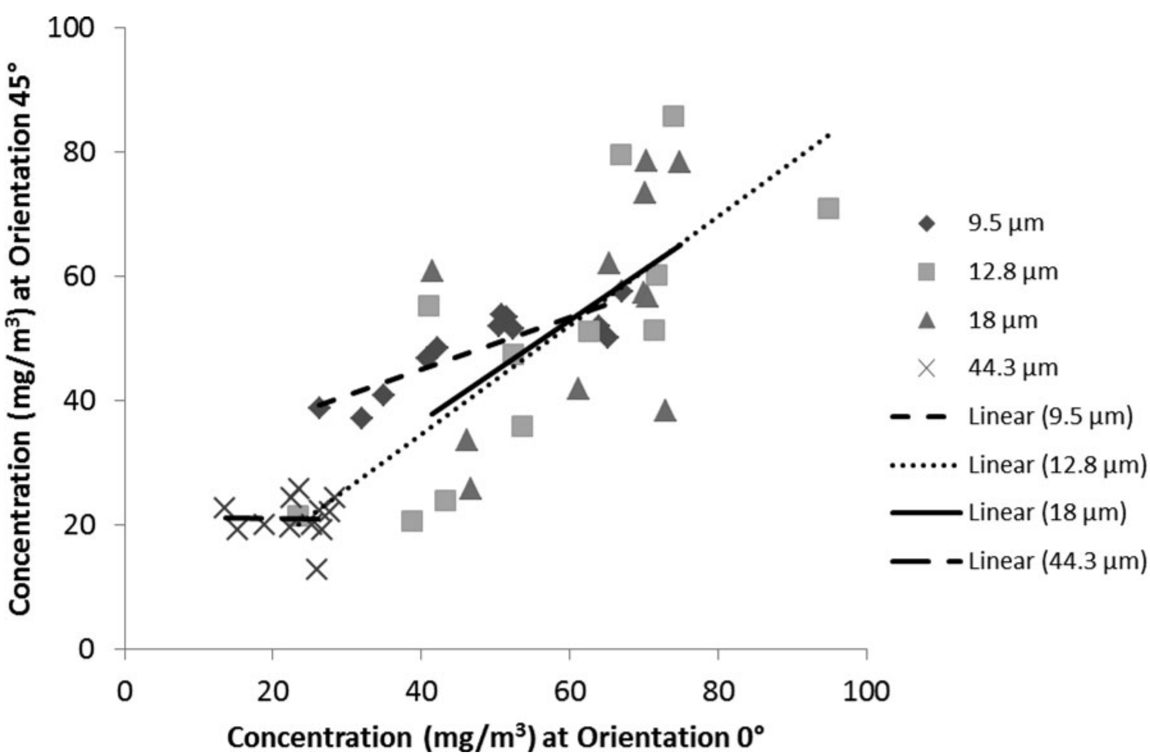

FIGURE 2. Comparison of mass concentrations for cassette orientations at 45° from horizontal and horizontal 0°, for all particle sizes 9.5 μm (black diamond), 12.8 μm (light grey square), 18 μm (dark grey triangle), and 44.3 μm (grey X). The various lines show linear regression for 9.5 μm (short dashes), 12.8 μm (dotted line), 18 μm (solid line), and 44.3 μm (long dashes).

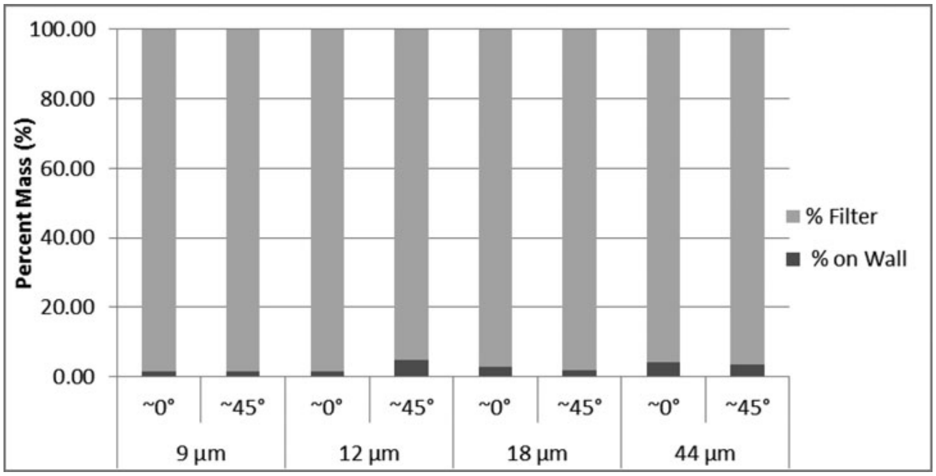

FIGURE 3. Percent of total mass collected on the cassette filter (light grey) and the interior wall (black) for orientations 45° from horizontal and 0°, horizontal, for four particle sizes.

not effectively sample the aerosol. Second, although there was the possibility that the cassettes may have been placed close enough together to interfere with each other, it was determined that the flow rate was low enough (i.e., its reach did not extend to the adjacent samplers) that placement of the cassettes should not have interfered with each other.

An additional consideration is that only a minimal amount of particle mass was collected on the interior sampler walls, which may have been due to wiping the walls with a dry 25-mm glass fiber filter. If a solvent, such as isopropyl alcohol, was also used with the wipe filter, collection of the wall deposits may have improved.

Strengths of this study include that the selection of particle size for each sampling event was carried out at random. Also, the particles were dispersed uniformly in a controlled low-wind speed tunnel with the cassettes at specific angles on a rotating mannequin for a specified amount of time. This study design provided an accurate representation of human exposure in workplace environments. An additional strength was the inclusion of the wall deposits. A limitation of this study includes not having performed isokinetic sampling to assess actual sampling efficiency. However, it was decided that isokinetic sampling was not needed because we were comparing the sampler orientation, not the efficiency. The effect of orientation was assessed using the concentration alone. Another limitation was the sample size (n = 94). A study collecting a greater number of samples at each orientation and for each particle size may be necessary to demonstrate a statistical difference in sampled concentration based on cassette orientation.

CONCLUSION

The results of this study indicate that there was no significant difference in concentrations collected by the CFC cassettes at orientations 45° from horizontal and horizontal 0°. These results also showed that the percent of mass collected on the interior walls was relatively low compared to the expected wall loses (up to 100%). These results imply that small changes in sampler orientation are unlikely to provide statistically significantly different concentration measurements.

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