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Comparison of a Simplified and Full-Size Mannequin for the Evaluation of Inhalable Sampler Performance

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A simplified mannequin was used to evaluate performance of the Institute of Occupational Medicine (IOM) personal sampler, and results were compared to those obtained using a full-size, rotating mannequin. The simplified mannequin, similar to that described by Witschger et al. (1998), was constructed using an inverted plastic wastebasket with dimensions of 33 cm wide × 20 cm deep × 20 cm high. IOM samplers mounted on both mannequins were exposed to narrowly-distributed aluminum oxide (Al_2O_3) test dust with aerodynamic diameters of 7, 22, 52, 82, and 116 μm. Results were obtained for three wind velocities: 0.4, 1.0, and 1.6 m/s. Sampler performance for the IOM sampler showed reasonable agreement with the ACGIH/ISO/CEN IPM sampling criteria when mounted on either mannequin. The two mannequins, however, showed opposite trends in aspiration efficiency with wind velocity. An increase in aspiration efficiency with an increase in wind velocity was found for the simplified mannequin, while the full-size mannequin gave a decrease in aspiration efficiency with increasing wind velocity. The effect was most apparent for particles larger than 50 μm.

INTRODUCTION

Within recent years, the American Conference of Governmental Industrial Hygienists (ACGIH), the International Organization for Standardization (ISO), and the Comité Européen de Normalisation (CEN) have agreed on sampling criteria for the inhalable particulate mass (IPM) fraction as outlined in the ACGIH 1999 TLVs and BEIs booklet (ACGIH 1999). IPM represents the fraction of ambient particles, as a function of size, capable of being inhaled. The IPM sampling criteria provide a physiologically based approach to sampling of aerosols that contain large particles. Aerosols, such as pesticides, metals, corrosives, and radioactive particles, can have their site of toxic action or absorption anywhere in the respiratory system. Personal sampling based on traditional methods for small particles does not accurately reflect worker exposure to large particles. It is a goal of the occupational health community to replace standards based on "total" dust measurement with IPM standards or other particle size-selective standards. To date, the ACGIH (1999) has adopted seven IPM-TLVs (Threshold Limit Values) and includes ten more in their "Notice of Intended Changes." Countries in the European Economic Community have also incorporated IPM criteria into the setting of occupational exposure standards (ISO 1995).

While this approach represents significant improvement in sampling methodology, only the Institute of Occupational Medicine (IOM) personal sampler (Mark and Vincent 1986) has been shown to match the IPM sampling criteria over the range of particle sizes and wind velocities encountered in the workplace environment. At present, one limitation on the development of new samplers to meet these criteria is the difficulty in evaluating sampler performance. Present methods require the use of a large cross section (1–4 m^2), low velocity (0.2–4.0 m/s) wind tunnel that can achieve a uniform concentration of large particles (10–100 μm) and can accommodate a full-size, full-torso mannequin. The latter is necessary because the performance of a sampler mounted on a person is sensitive to the direction and magnitude of external air motion. The complex airflow around a person affects the air motion in the vicinity of the sampler which, in turn, affects the performance (aspiration efficiency) of a sampler (Johnson et al. 1996; Rodes et al. 1995; Wood and Birkett 1979). This is the reason that full-size, full-torso mannequins are used for testing personal samplers. There are only a handful of such facilities in the world. Even when an adequate test system is available, there are many potential problems associated with maintaining uniform aerosol concentration and air velocity around a full-size, full-torso mannequin. Usually, the mannequin is rotated to provide orientation-averaged results for sampler performance regardless of wind direction.

Recently, two approaches have been taken to facilitate the evaluation of personal samplers for large particles. They are dimensional scaling and the use of a simplified mannequin. While dimensional scaling is conceptually appealing, it is a complicated endeavor and presents its own set of difficulties,

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which have been described by Ramachandran et al. (1998). Significant time saving can be achieved through the use of a simplified mannequin if it can provide results that correlate with measurements from a full-scale test system as described above. It would potentially allow the use of a smaller wind tunnel and eliminate the need for rotation of the mannequin. A previous study (Witschger et al. 1998) investigated the use of a simplified mannequin for the evaluation of personal samplers. They found that the air motion near the sampler inlets was similar to that for a full-size mannequin and that the measured sampler efficiency for 70 μm particles was not significantly different.

The objective of the present study was to compare the performance of the IOM sampler when mounted on a simplified mannequin with that when mounted on a full-size mannequin over a wide range of particle sizes (5–120 μm) and wind velocities (0.4–1.6 m/s).

EXPERIMENTAL

All measurements were made using an existing open-cycle, closed-jet, low-velocity wind tunnel (Hinds and Kuo 1995). The wind tunnel has a 1.6 × 1.6 m cross section and was operated at three wind velocities (0.4, 1.0, 1.6 m/s). A full-size, full-torso mannequin was mounted in the test section of the wind tunnel. The mannequin has average adult proportions, is 1.03 m high, and was positioned so that its mouth was at the center of the wind tunnel cross section. Depending on its angle of rotation, the mannequin blocks between 4 and 11% of the cross-sectional area of the wind tunnel. This is within the range of 10% recommended by Vincent (1989) to minimize distortion of the freestream. This mannequin was used in other studies to evaluate inhalability of large particles, as well as the sampler performance study described here. When used to determine inhalability, the mouth inlet of the mannequin is connected to a mechanical breathing machine that simulates human breathing. For the purpose of this study, only the results for sampler performance were used. To provide orientation-averaged results, the full-size mannequin was slowly rotated (0.06 rpm) once during a sampling run.

The simplified mannequin was fashioned from a plastic wastebasket (Rubbermaid, No. 2596). It has a three-dimensional body with rounded corners. The wastebasket was inverted and cut down to match the dimensions used by Witschger et al. (1998), 33 cm wide × 20 cm deep × 20 cm high. The simplified mannequin blocks 2.6% of the wind tunnel cross section. During sampling, it replaced the full-size mannequin in the wind tunnel but did not rotate. To measure the aerosol concentration in the wind tunnel, three isokinetic samplers were positioned 0.3 m to the sides and above the top of the head of the full-size mannequin or the "body" of the simplified mannequin.

The isokinetic sampler locations had previously been determined to be the closest location to the mannequin's mouth for which the presence or absence of the mannequin had no affect on air velocity direction or measured concentration (Hinds and Kuo 1995). For the simplified mannequin, testing with a smoke tube revealed that the presence of the simplified mannequin caused the air to diverge slightly and enter the lateral isokinetic samplers at an angle of 6–7° to the straight-in direction. For the conditions of air velocity and particle size used here, this amount of misalignment produces a calculated sampling error of 1% for all conditions (Hinds 1999).

For the full-size mannequin, the IOM personal sampler was attached to the lapel of the mannequin (within 30 cm of the mouth). The simplified mannequin was positioned so that the IOM samplers were between the two lateral isokinetic samplers and at the same height as the breathing zone of the full-size mannequin. Orientation-averaged results for the simplified mannequin were calculated as the arithmetic average of the values for 0°, 90°, 180°, and 270° with respect to wind direction. The IOM samplers were operated at a sampling flow rate of 2.0 L/min and were fitted with 25 mm glass fiber filters.

Five narrowly-distributed particle sizes ($1.16 < \mathrm{GSD} < 1.34$) of test aerosol were used. The test dust was Al_2O_3 optical powder (Norton Company, Worcester, MA and General Abrasives/Treibacher, Inc., Niagara Falls, NY) and the aerodynamic diameters were 7, 22, 52, 82, and 116 μm. To minimize electrostatic effects, the supply air to the aerosol generator was humidified and an adjustable ion generator was used to mix negative ions with the aerosol stream. The ion generator is cylindrical with an axial aerosol stream, a center electrode, and four fine, peripheral electrodes. Adjusting the voltage between the center and peripheral electrodes produces the requisite concentration of ions. Details are given by Hinds and Kennedy (2000). The mass concentration in the wind tunnel ranged from 50–200 mg/m^3. Variation in concentration was attributed to the range of wind velocities used and to size-dependent loss of dust in the aerosol delivery system. The dust concentration was uniform within 15% over the test area of the wind tunnel. The temporal variation in concentration does not exceed 10% (Hinds and Kuo 1995).

Aspiration efficiency of the IOM sampler was determined by comparing the average mass concentration determined by the personal sampler(s) to that measured by the isokinetic samplers. All particles entering the inlet of a given sampler were included in the sample. The aspiration efficiency of the samplers on the simplified mannequin was then compared to that for the sampler on the full-size mannequin.

The experiments were conducted at three wind velocities: 0.4, 1.0, and 1.6 m/s. Horizontal and vertical 11 point traverses across the wind tunnel were used to evaluate the uniformity of the wind velocity in the wind tunnel. It was found to be uniform within 10% over the test area. The wind tunnel meets the guidelines of the European Economic Community for testing IPM samplers (CEN 1993) and shows good performance over the particle size range of 10 to 145 μm.

The size distribution of the aluminum oxide test aerosol particles was determined by optical microscopy. A dynamic shape factor for these irregular particles was determined by measuring the terminal settling velocity in water of individual particles of known physical dimensions. Particle size is expressed as mass median aerodynamic diameter (MMAD). A time-of-flight instrument (API, Hadley, MA) confirmed uniformity of the dynamic shape factor over the particle size range.

Tests were run for five particle sizes and three wind velocities for a total of 15 sampling conditions. Three replications for each set of conditions were performed.

RESULTS

Sampler performance for the IOM personal sampler indicated reasonable agreement with the IPM sampling criteria whether the sampler was mounted on a full-size mannequin or a simplified mannequin (Figure 1). However, the two mannequin set ups showed opposite trends with respect to wind velocity (Figures 2 and 3) for large particles. Figure 2 shows aspiration efficiency decreasing with increasing wind velocity for samplers attached to the full-size mannequin. As shown in Figure 3, when samplers are attached to the simplified mannequin, aspiration efficiency increases with increasing wind velocity.

The effect of wind velocity on aspiration efficiency is most pronounced for particles larger than 50 μm. Below that size, the trend of aspiration efficiency with wind velocity is unclear. Figure 4 shows aspiration efficiency for the two mannequins at a wind velocity of 0.4 m/s, a wind velocity more representative of average indoor conditions than the other velocities used. For the largest particles, this wind velocity shows the greatest difference in aspiration efficiency for the two mannequins. For particles with aerodynamic diameter larger than 50 μm, the use of a simplified mannequin at low wind velocity conditions (0.4 m/s) gave an average aspiration efficiency that is approximately 35% of that for the full-size mannequin. At this velocity and particle size range the simplified mannequin more closely matches the IPM criteria curve than the full-size mannequin does. For a wind velocity of 1.6 m/s, the average aspiration efficiency for the largest particles is within 10% for the two mannequins.

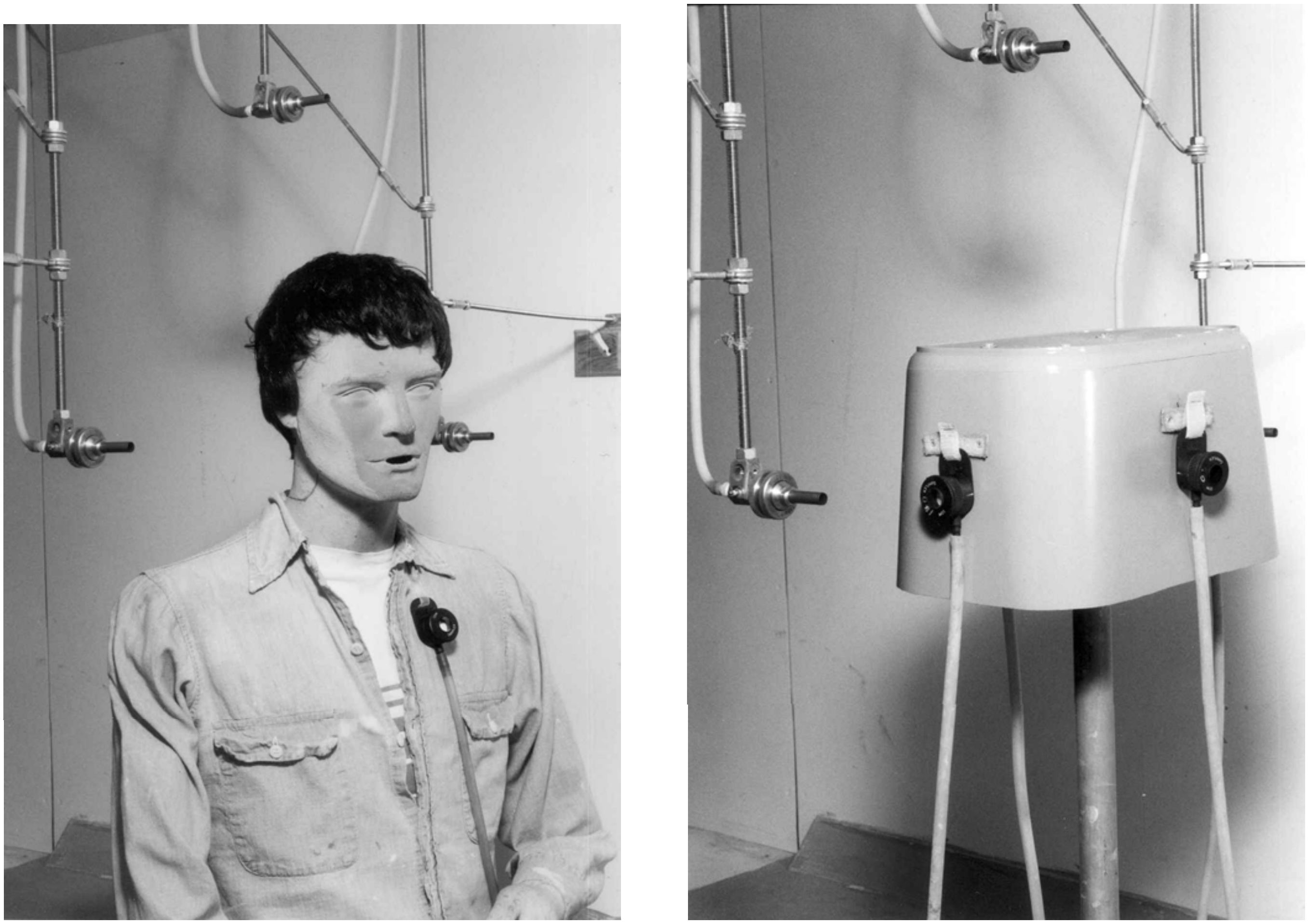
(*a*) (*b*)

Figure 1. (a) Photograph of full-size mannequin. (b) Photograph of simplified mannequin.

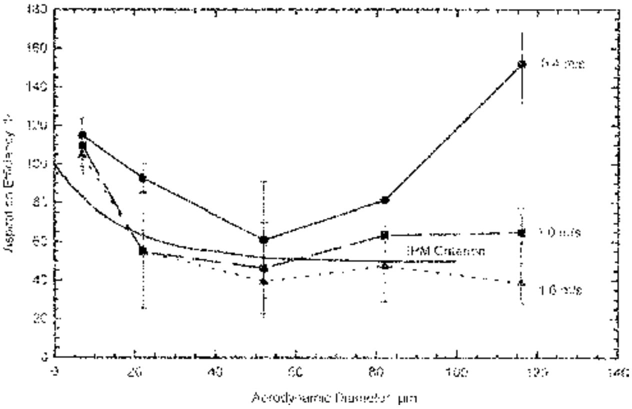

Figure 2. Aspiration efficiency versus aerodynamic particle size for full-size mannequin at three wind velocities.

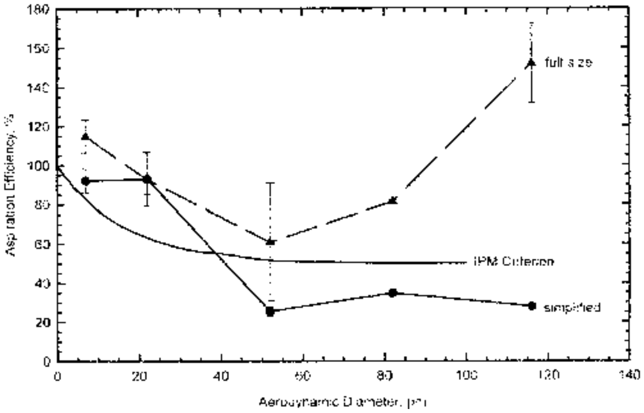

Figure 4. Comparison of aspiration efficiency of full-size and simplified mannequin at a wind velocity of 0.4 m/s.

DISCUSSION

As with all large-scale, low-velocity wind tunnel studies, there are sources of uncertainty and error in the experimental measurements. Although three replications for each set of conditions were made to reduce statistical error, the error bars are largely compared to the differences between the results for the two mannequins. A larger number of replications would reduce this uncertainty and better define the trends. The Al_2O_3 particles are difficult to size, and the charge on the particles must be reduced to prevent electrostatic effects. Any error in these factors will affect the aspiration efficiency results, although it should affect sampler performance for both mannequins similarly.

One reason for the opposite trends in sampler performance with wind velocity for large particles may be the difference between the methods used to obtain orientation-averaged results. The rotating full-size mannequin allows sampling at all angles with respect to wind direction; the simplified mannequin relies on averaging of samples taken at only four angles relative to the wind direction (0°, 90°, 180°, and 270°). This may overrepresent the contribution of the facing-the-wind orientation for large particles at high wind velocities compared to a sampler on a rotating mannequin.

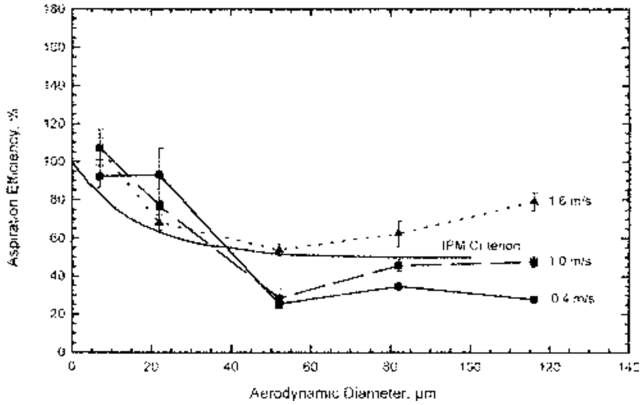

Figure 3. Aspiration efficiency versus aerodynamic particle size for simplified mannequin at three wind velocities.

Another possible explanation is associated with the mechanisms of aspiration when the sampler is facing the wind. For the largest particles, the most important orientation by far is facing-the-wind or 0° orientation. For both mannequins the orientation-averaged aspiration efficiency is dominated by the aspiration efficiency at 0° orientation. Two effects influence aspiration efficiency at 0°. The first is inertial projection of approaching particles into the personal sampler inlet. This mechanism will increase aspiration efficiency with increasing wind velocity as additional particles, not originally in the sampled air volume, get thrown into the sampler inlet. The stopping distance for the largest particle size ranged from 16 to 66 mm for the slowest and fastest wind velocities used.

The second effect is due to the deflected air current that flows vertically past the personal sampler. When the full-size mannequin is facing the wind the presence of the torso causes an upward flow of air in the vicinity of the personal sampler on the torso (Witschger et al. 1998). The physical dimensions of the mannequin force the wind to flow vertically and laterally to get around the mannequin. The deflected air current causes particles to approach the personal sampler inlet at an angle, which reduces its aspiration efficiency (Vincent 1987; Vincent and Mark 1982). This is why samplers mounted on a mannequin, or a person, perform differently than isolated samplers and why personal samplers should be tested on a mannequin (Vincent 1989). Because of the larger size and greater vertical dimension of the full-size mannequin, the deflected air current is stronger for the full-size mannequin than for the simplified mannequin (Witschger et al. 1998). At a position 75 mm in front of the personal sampler location, Witschger et al. (1998) found the vertical air current to be approximately five times stronger for the full-size mannequin than for the simplified mannequin. The influence of the deflected air current may be enhanced by the fact that the IOM sampler sticks out from the surface of the mannequin 28 mm.

These competing effects could account for the observed trends in aspiration efficiency with wind velocity for the two mannequins. The weaker vertical air current for the simplified mannequin would have a relatively small effect on the straight-in inertial projection mechanism. Consequently, the inertial projection mechanism will increase aspiration efficiency with increasing wind velocity for the simplified mannequin. Because the vertical air current is significantly stronger for the full-size mannequin, it could cause an offsetting decrease in the aspiration efficiency with wind velocity of a sampler mounted on the full-size mannequin. Apparently the vertical air current is strong enough to create a net reduction in aspiration efficiency with wind velocity of large particles with increasing wind velocity for 0° orientation.

Another possible explanation, closely related to the one given above, has to do with the location of the stagnation point for 0° orientation. This is the point on the surface of the mannequin where there is no lateral velocity. The inertia projection mechanism would be most effective at this point. For the simplified mannequin, the stagnation point would likely be the midpoint of the flat panel facing the wind, which is also the location of the personal sampler inlet. For the full-size mannequin, it would likely be near the midpoint of the torso some 0.2–0.3 m below the sampler inlet. This would cause no or low lateral or vertical velocity for the simplified mannequin at the location of the sampler inlet and a higher lateral or vertical velocity for the full-size mannequin at its sampler location. This could account for the observed trend of aspiration efficiency with wind velocity, as described above.

CONCLUSION

In the evaluation of IOM personal sampler performance, both the simplified mannequin and the full-size mannequin gave results that are reasonably close to the IPM sampling criteria for $d_a < 80$ μm and wind velocity from 0.4 to 1.6 m/s. Opposing trends in aspiration efficiency with wind velocity were found for particles larger than 50 μm. For the simplified mannequin, aspiration efficiency increased with increasing wind velocity for large particles. When the IOM sampler was mounted on a full-size mannequin, the aspiration efficiency decreased with increasing wind velocity for these particles. The results indicate that the simplified mannequin can be used to evaluate personal inhalable sampler performance when aerodynamic diameter is 80 μm and the wind velocities are in the range 0.4–1.6 m/s. For larger particles, the simplified mannequin approximates results obtained on the full-size mannequin only at a wind velocity of 1.0 m/s and is therefore limited in its usefulness for testing personal inhalable samplers.

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