Pergamon
www.elsevier.com/locate/jaerosci

PII: S0021-8502(99)00037-3

J. Aerosol Sci. Vol. 31, No. 2, pp. 169–179, 2000
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Printed in Great Britain
0021-8502/99/$ - see front matter

MEASUREMENT OF THE SAMPLING EFFICIENCY OF PERSONAL INHALABLE AEROSOL SAMPLERS USING A SIMPLIFIED PROTOCOL

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(*First received* 10 *December* 1998; *and in final form* 26 *March* 1999)

Abstract—Traditional protocols for the performance evaluation of personal inhalable aerosol samplers utilize full-size manikins and large cross-section wind tunnels. Thus, these sampler evaluation procedures are complex, very costly, and time consuming. In addition, it is difficult to provide an adequately uniform wind velocity and aerosol concentration over large cross-section wind tunnels. A simplified test protocol, developed in our recent studies, is evaluated in this paper. The protocol is based on a three-dimensional rectangular simplified torso that simulates the dimensions of the human chest. This arrangement allows simultaneous measurement in four discrete orientations to the wind, thus providing useful orientation-dependent sampler information and possibly reducing the number of measurements needed. Sampling efficiencies of four personal inhalable aerosol samplers (the IOM, GSP, 37-mm closed-face cassette, and the button sampler) were measured using the simplified test protocol and the traditional approach for three particle sizes (7, 29, and 70 μm) in four inlet orientations to the wind (0, 90, 180, and 270°) and two wind velocities (0.5 and 2.0 $\mathrm{m\,s^{-1}}$). It was found that when these samplers were mounted on the simplified torso versus the full-size manikin, the sampling efficiencies responded to changes in the sampling conditions in the same way regardless of whether the samplers were mounted on the simplified torso or the full-size manikin. Also, the sampling efficiencies were found not to be statistically different when the samplers were mounted on the simplified torso versus the full-size manikin. Thus, the simplified test protocol was shown to be suitable for the performance evaluation of personal inhalable aerosol samplers. © 1999 Elsevier Science Ltd. All rights reserved

INTRODUCTION

Personal inhalable aerosol samplers are widely used for personal exposure assessment in the workplace. The development of these samplers has followed a varied course over the past 25 years, often not taking into account aerosol particle behavior under workplace sampling conditions. Therefore, various inhalable aerosol samplers were found to produce widely different measured concentrations. In recent years, several groups, including the American Conference of Governmental Industrial Hygienists (ACGIH), the European Standards Committee (CEN), and the International Standards Organization (ISO), have reached consensus regarding the criteria for personal inhalable aerosol sampling (ACGIH, 1999; CEN, 1993; and ISO, 1995). The ACGIH/CEN/ISO convention defined in the range of 0–100 μm represents the direction-averaged sampling efficiency of a manikin nose and mouth at a wind speed typical of workplace conditions. Thus, samplers placed on a manikin in a wind tunnel are expected to match the sampling efficiency defined by the convention, while exhibiting low dependence on the wind velocity and direction (e.g., CEN, 1997).

A wide variety of personal inhalable aerosol samplers are presently used in the United States and Europe. The most commonly used samplers were evaluated by Kenny *et al.* (1997), including the 37 mm cassette (closed-faced and open-face, SKC Inc., Eighty Four, PA), the CIP10-I sampler (Arelco, Fontenay-Sous-Bois, France), the GSP sampler

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(Ströhlein GmbH, Kaarst, Germany), the IOM sampler (SKC Inc., Eighty Four, PA), the PERSPEC aerosol spectrometer (Lavoro e Ambiente, Bologna, Italy), the PAS-6 sampler (produced by the Department of Air Quality, Wageningen Agricultural University, PO Box 8129, 6700 EV Wageningen, The Netherlands), and the seven-hole sampler (SKC Inc., Eighty Four, PA, and Casella Ltd., London, UK). The designs of these samplers differ significantly from one another. Thus, wind velocity and direction, inlet size and geometry, aerosol particle size and bounce properties, and particle and sampler charge affect the samplers' performance in different ways. As a result, the samplers' bias relative to the inhalable convention and their precision (repeatability of results under identical sampling conditions) differ widely from one device to another. The ultimate goal of the ACGIH/CEN/ISO convention is to promote the development of samplers that provide comparable results. However, considering the likelihood that traditional samplers will continue to be used for some time, it is desirable to evaluate each of these, as well as newly designed samplers, to estimate its bias relative to the inhalable convention.

Traditional protocols used by different researchers for the performance evaluation of the personal inhalable aerosol samplers possess different degrees of sophistication. All the protocols have had some common features: the test samplers are mounted on a full-size human-shaped manikin (Vincent, 1989) and the manikin is rotated (continuously or in a stepwise fashion), yielding direction-averaged data in horizontal plane. Buchan *et al.* (1986) used this approach to evaluate the sampling efficiency of several modifications of the 37-mm filter cassette. Botham *et al.* (1991) used a full-size manikin with a breathing machine capable of simulating different breathing patterns. Kenny *et al.* (1997) also used a full-size rotating breathing manikin in their sampler performance evaluation study. Even more complex experimental arrangements have been utilized. For instance, Johnson *et al.* (1996) investigated effects of the body-generated heat on the airflow around the human body. It was found that at the wind velocities above $0.5\ \mathrm{m\,s^{-1}}$ the heated air had a minimal effect on the airflow patterns near the human body. At the lower wind velocities it primarily increased the upward airflow component (by about $0.2\ \mathrm{m\,s^{-1}}$).

Because of the physical dimensions of full-size manikins, the sampler evaluation must be conducted in large cross-section wind tunnels. For example, Kenny *et al.* (1997) used a 2.5×2.5 m cross-sectional area wind tunnel located at AEA Technology in Harwell, United Kingdom. The use of large wind tunnels is costly and time consuming. Hinds and Kuo (1995) reported that the total cost of the $1.6 \times 1.6\ \mathrm{m}^2$ system installed at UCLA was $18,000. A further disadvantage of large wind tunnels is that air velocity and aerosol uniformity are difficult to maintain across the cross section of the tunnel. Ramachandran *et al.* (1998) indicated that the aerosol concentration in large wind tunnels can vary by up to $\pm 20\%$ spatially and $\pm 15\%$ with time, depending on the particle size. The coefficient of variation reported by Hoover *et al.* (1996) was 11% over the central $30 \times 30\ \mathrm{cm}^2$ of the $76 \times 76\ \mathrm{cm}^2$ test area. The uniformity of aerosol concentration reported by Hinds and Kuo (1995) was $\pm 15\%$. Kenny *et al.* (1997) acknowledged that it is "extremely difficult to generate test aerosols with an acceptable degree of homogeneity and stability in the large cross-section wind tunnel".

These arguments suggest a need for alternative approaches to testing personal inhalable aerosol samplers. Two such approaches have been recently published. Ramachandran *et al.* (1998) proposed using scaling relationships and semi-empirical aspiration models that would allow the use of small-scale models of the samplers and manikin in a smaller wind tunnel, using smaller particles. This addresses spatial and temporal concentration uniformity issues and allows substantial reduction of the initial investment needed to build the experimental system. Further work is being carried out to validate this approach. Another approach introduced in our recent publication (Witschger *et al.*, 1998) proposed a simplified test protocol that can be utilized in a smaller wind tunnel. This protocol allows significant reduction of the number of experiments needed for the performance evaluation of personal aerosol samplers. It also allows the use of a significantly smaller wind tunnel.

Simplified test torso

The basis of the simplified test protocol is a simplified test torso. It is a three-dimensional rectangular body (33 cm width × 21 cm height × 21 cm depth) featuring rounded edges (with 1.5 cm radius of curvature) to reduce turbulence effects. The rationale behind the simplified test torso is to simulate the middle part of the human torso where inhalable aerosol samplers are usually mounted. This simplification seems feasible, as most of the existing evaluation protocols ignore aerodynamic effects of the arms, neck, and head. Secondary features (e.g., breathing and thermal effects) are also ignored for simplicity.

To correctly estimate the geometrical dimensions of the human upper body when designing the simplified torso, anthropometrical databases were used. Because of the scarcity of civilian anthropometric data, the Anthropometric Survey of U.S. Army Personnel (ANSUR) reported by Gordon *et al.* (1989) was used. The ANSUR indicates chest breadths of 30 and 28.5 cm for males and females, respectively. Generally, application of military anthropometric data to civilian population is somewhat limited due to fitness and age restrictions that the military imposes on its personnel. To account for these limitations as well as body size that is larger in the civilian population, the width of the simplified torso was increased to 33 cm. To arrive at the height of the simplified torso, waist height (at the navel) was subtracted from the chest height (at the armpits). Both pieces of data reported in the ANSUR. The result was 21 cm for males and 19.6 cm for females. The higher of the two, 21 cm, was chosen for the simplified torso. It should be noted that the selected height of the simplified torso did not intend to simulate the full height of the human torso. The depth of the simplified body, being the least important aerodynamically, was chosen more arbitrarily to be 21 cm.

Sampling in specific orientations as opposed to rotation averaging

In contrast to other current inhalable aerosol sampler evaluation protocols, the simplified protocol does not involve continuously rotating torso. Instead, samplers are mounted on the front, back and both side faces of the simplified torso, thus measuring in four directions (0, 90, 180, and 270° to the wind) simultaneously. The first of these sampling orientations represents the most favorable sampling condition (aspiration facing the wind) when the highest sampling efficiency can be expected. The second and fourth orientations represent the least favorable sampling situation since the smallest possible area of the inlet faces the incoming aerosol flow field. The third orientation presents sampling from the wake of the torso, which creates air turbulence and possibly a nearly stagnant zone at low wind speed. For these reasons, we believe that these four discrete orientations are of principal interest in personal aerosol sampling. Also, they yield the minimum set of data points from which the following linear combination (weighted sum) can be constructed for a meaningful comparison with data obtained by traditional direction-averaged (continuous rotation) methods:

$$E_{\text{dir-avg}} = \tfrac{1}{4}\,(E_0 + E_{90} + E_{180} + E_{270}), \tag{1}$$

where E_0, E_{90}, E_{180}, and E_{270} are the sampling efficiencies measured at 0, 90, 180, and 270°, respectively. In the experiments described here, the sampling efficiencies at 90 and 270° were assumed to be equal and thus $E_{90} + E_{270}$ could be replaced by 2 E_{90}. This scheme weights the four individual orientations equally due to their equal relative time contribution. While it is recognized that the sampling efficiency is likely to be a complex function of the actual orientation, the weighting scheme in equation (1) represents a reasonable approximation to the average obtained by continuous rotation. While this approach is a simplification of the continuous rotation approach, it provides additional information about sampling in different orientations. In the workplace, some specific orientations may be encountered more frequently than others. Hence, the weights in equation (1) may be adjusted to more accurately reflect the sampling environment. CEN (1997) stipulates that no less than four stepwise sampling efficiency values are needed to estimate the direction-averaged sampling efficiency. Thus, implementing the no-rotation procedure not only reduces the number of experiments by a factor of four, but also yields additional information on the sampler performance in four orientations of principal interest. This information is lost if a manikin continuously rotates. At the same time, while omitting other orientations that are frequently tested (e.g., 45, 135, and 225°), this procedure yields a result that accurately reflects the "true" direction-averaged value.

Previous results

Witschger *et al.* (1998) conducted a comparative airflow study of the simplified torso and full-size manikin in a large cross-section wind tunnel. The airflow patterns around the simplified test body and full-size manikin were found to be similar when tested with and without samplers mounted on them and dependent on the samplers' location on the manikin. This conclusion holds true for all four principal orientations and wind velocities of 0.5 and 2.0 $\mathrm{m\,s^{-1}}$. In addition to the airflow results, this study reported limited data on the aerosol sampling efficiency of the GSP samplers exposed to 70 μm aerosol particles. The sampling efficiency was determined when the GSP samplers were mounted on the simplified torso and the full-size manikin, respectively. No statistically significant difference was found between sampling efficiencies of the GSP samplers mounted on both types of bodies for the particle size tested. These results showed promise, but necessitated a more detailed comparison involving several personal inhalable aerosol samplers and a wider range of particle sizes. The present study was initiated to generate sampling efficiency data for the samplers mounted on the simplified torso in a large wind tunnel. This step is needed prior to testing the simplified protocol in a small wind tunnel.

EXPERIMENTAL DESIGN

The hypothesis of this study was that the aerosol sampling efficiency of personal inhalable aerosol samplers is not statistically different when the samplers are tested at several particle sizes and wind speeds in accordance with the simplified test protocol (i.e. mounted on the simplified torso), as compared to when they are mounted on a full-size manikin. Table 1 summarizes the experimental variables involved in this study.

The simplified test protocol was evaluated using four personal inhalable aerosol samplers: the IOM and GSP samplers were chosen because they demonstrated the best accuracy and precision among several widely used samplers evaluated by Kenny *et al.* (1997); the 37-mm closed-face cassette (ours were made of conductive plastic by Omega Specialty Instrument Co., Chelmsford, MA) was chosen because it is the most ubiquitous personal inhalable aerosol sampler in the U.S. today; and the button sampler (SKC Inc., Eighty Four, PA) was chosen because its sampling efficiency was found to have low sensitivity to wind direction and velocity (Kalatoor *et al.*, 1995; Aizenberg *et al.*, 1998; Aizenberg *et al.*, 1999). The samplers were placed on the two bodies: the full-size manikin and the simplified torso. This was accomplished by the means of small screws to rigidly mount the samplers during the experiments. The samplers were mounted within the breathing zone of the full-size manikin. When mounted on the simplified torso, the samplers were placed at equal distances from its top and bottom faces, at the same height as on the full-size manikin (37 cm from the floor of the wind tunnel). The simplified torso was mounted on a base approximately 20 cm high to make up the difference in height. Three nearly-monodispersed ($\sigma_g \approx 1.35$) aerosols with mass median aerodynamic diameters of 7, 29, and 70 μm were used.

Table 1. Experimental variables

Samplers	The IOM, GSP, 37-mm closed-face cassette, button
Orientations to the wind	0, 90, 180, 270°
Particle sizes (μm)	7, 29, 70
Wind velocities ($\mathrm{m\,s^{-1}}$)	0.5, 2.0

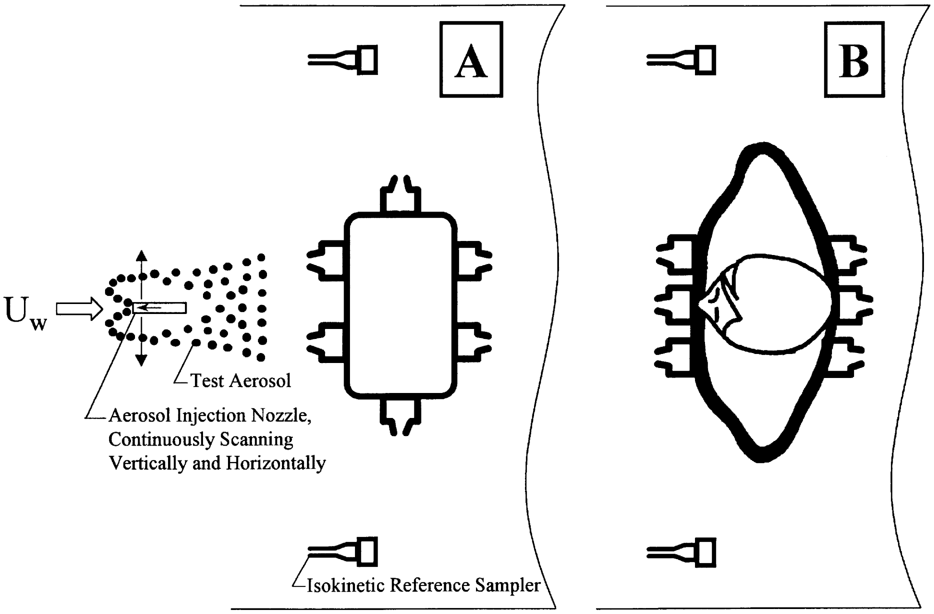

Fig. 1. Experimental system. (A) Simplified torso, (B) full-size manikin.

The greatest potential for simplification of the traditional sampler performance evaluation protocol is in decreasing the number of particle sizes used. There has been no national or international regulatory or consensual standard as to which or how many particle sizes should be used. While we recognize that more sizes are better as far as accuracy and reliability of a sampler evaluation are concerned, choosing the particle sizes was traditionally left to the researcher's judgment. However, this project was concerned with the method itself, not the actual evaluation of the samplers. Based on the time constraints, only the three above-mentioned particle sizes were tested. They were representative of the lower, intermediate, and upper ranges of the particle sizes included in the inhalable fraction.

The samplers were tested at wind velocities (U_w) of 0.5 and 2.0 $\mathrm{m\,s^{-1}}$. The former is representative of indoor air velocity, while the latter represents outdoor air conditions. Baldwin and Maynard (1998) reported that indoor workplace air velocities were almost always less than 1 $\mathrm{m\,s^{-1}}$, while outdoor velocities were often greater than 1 $\mathrm{m\,s^{-1}}$. Finally, the sampling was conducted in four "principal" directions (0, 90, 180, and 270° to the wind). These orientations were chosen because they are intrinsic to the simplified test protocol. However, because both full-size manikin and simplified torso are symmetrical, the 90 and 270° orientations were treated as the same for the purpose of the statistical analysis. A paired *t*-test of the sampling efficiency values obtained in these orientations yielded a *p*-value of 0.34, thus confirming the above approach.

The experimental setup is schematically presented in the Fig. 1A and B. It is similar to the setup used by Witschger *et al.* (1998) and Aizenberg *et al.* (1999). Six samplers were mounted on the full-size manikin (three on the front, three on the back). Similarly, six samplers were mounted on the simplified torso (two on the front, two on the back, and one on each of the side faces). To reduce the random error, samplers of different types were mounted next to each other in the same test. At least three repeats of each experiment were conducted and results were averaged for each sampler under every sampling condition.

Either the full-size manikin or the simplified torso, each with samplers, was placed in the working section of the wind tunnel (Fig. 1A and B). Aerosol was injected into the working section of the wind tunnel approximately 1 m upstream of the test bodies. The injection occurred in the direction opposite to the airflow. This arrangement reduced the undesirable projection of possible particle agglomerates directly into the sampler inlets.

The reference concentration in the wind tunnel was determined using sharp-edged isokinetic samplers (two per experiment) located at the same height and plane as the test samplers (Fig. 1A and B). The reference samplers were placed symmetrically on both sides of each body at a distance of 20 cm from the left and right edges of the manikin and 47 cm from the simplified torso. Witschger *et al.* (1998) showed that at these distances the flow field was not significantly disturbed by the presence of the test body. For different wind tunnels, other appropriate locations of the reference samplers may be used. The isokinetic samplers operated at flow rates of 2.5 and 10 l min^{-1} (at wind velocities of 0.5 and 2.0 $\mathrm{m\,s}^{-1}$, respectively). A high-volume pump created the vacuum for these flow rates and flow rates of 2, 3.5, 2.25, and 4 l min^{-1} (for the IOM, GSP, 37-mm closed-face cassette, and the button samplers, respectively) through appropriate critical orifices. Direction-specific sampling efficiency of each test sampler was calculated as the ratio of the aerosol concentration measured by this sampler to the aerosol concentration yielded by the isokinetic samplers (average of two). The direction-averaged sampling efficiency was calculated using equation (1).

The experiments were carried out in a large cross-section (122 cm high by 183 cm wide) wind tunnel located at the National Institute for Occupational Safety and Health (NIOSH) in Cincinnati, OH. The wind tunnel was capable of generating wind velocities of up to 2.0 $\mathrm{m\,s}^{-1}$. A honeycomb was installed as a flow straightener approximately 0.6 m upstream of the aerosol injection nozzle to induce uniform airflow. The air velocity in the vicinity of the sampler inlets was uniform to within 5%, and the turbulence intensity (the ratio of the time-averaged velocity fluctuations to the mean velocity) was less than 6% for both wind velocities (Witschger *et al.*, 1998). The aerosol injection nozzle was mounted on a scanning system that traversed most of the cross-section of the wind tunnel (65 cm high by 127 cm wide), resulting in a uniform cross-section aerosol concentration when averaged over the traverse period. Three traverses per experiment were made for a total duration of 2.5 hr. The uniformity of the particle concentration was determined throughout the experiments using 10 isokinetic samplers positioned to cover most of the test area cross-section. Table 2 presents the coefficients of variation of aerosol concentration measured by ten isokinetic samplers in the sampling plane at different particle sizes. Aerosol concentration uniformity in this wind tunnel was comparable to those of the wind tunnels designed for similar purposes at Nancy, France (10%, Witschger *et al.*, 1997) and UCLA (15%, Hinds and Kuo, 1995).

Aluminum oxide (alumina) particles, CAS# 1344-28-1 (Fusco Abrasive Systems, Inc., Compton, CA) were used as test aerosols. A sedigraph (model 5000 Sedigraph, Micromeritics Instrument Corp., Norcross, GA) was utilized to measure the particle size distribution of the test particles. The aerosols were generated by a brush generation system (model RBG-1000, PALAS GmbH, Karlsruhe, Germany) capable of dispersing aerosols in the range of 0.1–100 μm. The generator output was exposed to the charge-neutralizing discharge of an airflow controller (model AFC-2, Richmond Static Control Services Inc., Palm Springs, CA).

The particles were collected on 37- and 25-mm glass-fiber filters (GFF). Because the GFF filters were susceptible to changes in temperature and humidity, they were equilibrated before and after the experiments in a climate-controlled room (temperature $= 24 \pm 2$°C;

Table 2. Coefficients of variation of aerosol concentration across the wind tunnel at $H = 37$ cm* (%)

Wind velocity, U_w ($\mathrm{m\,s}^{-1}$)	Aerodynamic particle diameter (μm)		
	7	29	70
0.5	8.7	12.2	7.8
2	5.2	6.3	11

*Sampler inlets were placed at this height.

relative humidity = 55 ± 3%) for at least 4 h. No electrostatic effects associated with the GFF filter material were observed. The mass collected on the filter was determined by gravimetric analysis as described in NIOSH method 0500 (NIOSH, 1994), using an analytical balance (model AT20, Mettler Toledo Inc., Hightstown, NJ). The limits of detection and quantitation (64 and 214 μg per sample, respectively) were those determined by Witschger *et al.* (1998).

All experiments were conducted in a completely randomized fashion. Some of the combinations of the experimental variables had more than three repeats; thus, statistical procedures associated with an unbalanced design were implemented. A significance level of 95% was maintained.

RESULTS AND DISCUSSION

Data are presented below on direction-averaged and direction-specific sampling efficiencies of the four test samplers. Two types of data analysis were conducted: Analysis of Variance (ANOVA) was used to compare the sampling efficiency values between two types of bodies for all samplers and Correlation Analysis was used to examine each sampler's sampling efficiency.

Analysis of variance of the direction-specific sampling efficiencies

More than 650 discrete sampling efficiency data points were obtained with the four test samplers, the full-size manikin, and simplified torso, two wind velocities, four sampling orientations, and three particle sizes. The central hypothesis of this study—that the sampling efficiency of a personal inhalable aerosol sampler is not statistically different when it is mounted on the full-size manikin versus the simplified torso—was confirmed. This conclusion is robust with respect to changes in other important factors considered in this study, i.e. wind velocity, sampler type, sampling orientation, and aerosol particle size.

A five-way factorial analysis of variance of the accumulated data was conducted to test this hypothesis. Data collected by all four samplers on both types of bodies under all sampling conditions (i.e. wind velocities of 0.5 and 2.0 m s^{-1}, sampling orientations of 0, 90, and 180°, and particle aerodynamic diameters of 7, 29, and 70 μm) were analyzed simultaneously. Because the sampling efficiency data are usually log-normally distributed due to random fluctuations in the sampling environment (Willeke and Baron, 1993), a logarithmic transformation was applied to produce normally distributed data. All five main effects (i.e. type of the torso, type of the sampler, wind velocity, sampling orientation, and particle size) and all interactions up to the fifth order were investigated for statistical significance, using the ANOVA procedure for a fully randomized design. After nonsignificant interactions were pooled with the error term, the overall F-ratio on the 107 degrees of freedom (df) and 547 error df (total of 654 observations) was equal to 72.04, having the corresponding p-value of 0.0001. The overall F-ratio is not interpretable and generally is used to estimate how well the model (as a whole) explains the variation about the grand mean (Winer, 1997). Detailed sources of variation (i.e. main effects and significant interactions) are of greater importance. As expected, particle size, sampling orientation, sampler type, and wind velocity were found to be highly statistically significant (p-values = 0.0001 for the first three main effects and 0.0023 for the U_w). However, the F-ratio for the torso type was equal to 1.27 on 1 df. The corresponding p-value (probability of obtaining this F-ratio by chance only) was 0.26. Thus, torso type is not a statistically significant effect in determining the variation of the sampling efficiency. Also, when the ANOVA procedure was used to compare sampling efficiencies measured on the full-size manikin versus the simplified torso, the data from all other sources of variation (i.e. type of the sampler, wind velocity, sampling orientation, and particle size) were combined. Thus, the conclusion of the preceding analysis did not depend on these factors.

Correlation analysis

The sets of data for the full-size manikin and simplified torso were tested using simultaneous correlation analysis at all three particle sizes. Table 3 summarizes results of this analysis. It shows that the correlation coefficients were above 0.92 with only two exceptions, when they were 0.74 and 0.88. Thus, there existed a strong positive correlation between sampling efficiency data from the manikin and simplified torso for each test sampler.

Graphical representation of the results of the correlation analysis between the simplified torso (Y-axis) and full-size manikin (X-axis) for the 37-mm cassette operated at 0.5 $\mathrm{m\,s^{-1}}$ wind velocity is provided in Fig. 2. Three distinct clusters of data (for 7, 29, and 70 μm) can be observed. Each cluster consists of the direction-specific sampling efficiency measured at 0, 90, and 180° to the wind and the calculated direction-averaged sampling efficiency. Sampling efficiency measured at 270° was combined with the one at 90° for the purposes of this analysis. Pearson's R^2 correlation coefficient (ratio of covariance over the product of the standard deviations of both data sets) based on the sampling efficiency data obtained at three discrete angles is 0.99. For the direction-averaged data it is 1.00. These R^2s indicate a very strong correlation between the sampling efficiency values when measured on the simplified torso and full-size manikin. Similar analysis was conducted on the data obtained with the other three samplers at both wind velocities, Table 3. The correlation analysis confirms that the sampling efficiencies of the test samplers respond to changes in the sampling conditions (such as the wind velocity and direction and the particle size) in the same way regardless of whether they are mounted on the simplified torso or the full-size manikin.

Table 3. Summary table of coefficients of correlation for the sampling efficiencies of four personal inhalable aerosol samplers measured under direction-specific (0, 90, 180°) and direction-averaged sampling conditions for all three particle sizes

Wind velocity, U_w ($\mathrm{m\,s^{-1}}$)	Orientation	37-mm closed-face cassette	IOM	GSP	Button
0.5	Direction-specific	0.99	0.88	0.92	0.93
	Direction-average	1.00	0.98	0.96	0.95
2	Direction-specific	0.93	0.97	0.98	0.74
	Direction-average	0.98	1.00	0.94	0.94

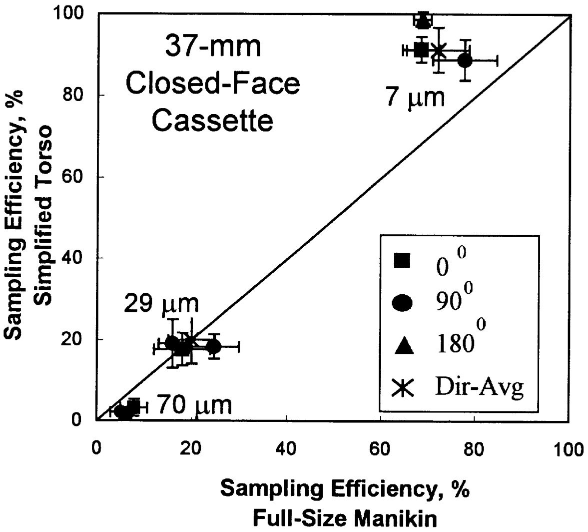

Fig. 2. Correlation of the direction-specific and direction-averaged sampling efficiencies of the 37-mm cassette. $U_w = 0.5\ \mathrm{m\,s^{-1}}$. The Pearson correlation coefficients are 0.99 and 1.00 for discrete angles and direction-averaged data, respectively.

Direction-averaged sampling efficiencies of the test samplers

Direction-averaged sampling efficiencies of the four inhalable aerosol samplers on both test bodies at $U_w = 0.5 \text{ m s}^{-1}$ as well as data published by Kenny *et al.* (1997) are presented in Fig. 3. It shows that the sampling efficiencies of all four inhalable samplers measured on the full-size manikin and the simplified torso follow each other and the Kenny *et al.* (1997) data comparatively well. This comparison of the sampling efficiencies, demonstrated by each of the samplers under the same conditions when mounted on the simplified torso versus the full-size manikin may be a better evidence of the adequacy of the simplified test protocol than the correlation analysis. The first three charts given in Fig. 3 present three sets of the sampling efficiency data obtained on the following: simplified torso, full-size manikin, and independent results obtained on the rotating breathing full-size manikin by Kenny *et al.* (1997). Because the button sampler was not yet available for testing in the latter study, the fourth chart gives only the first two sets of data. Also, because the Kenny *et al.* (1997) study used the traditional continuously rotating approach, experimental data obtained by us is presented only in calculated direction-averaged form. There are no error bars for the Kenny *et al.* (1997) data at 70 μm because this particle size was not included in that study. Instead, we have interpolated among available data points. The graphical representation of the ACGIH/ISO/CEN inhalable convention is given in each chart as a reference curve. As Fig. 3 shows, the calculated direction-averaged sampling efficiencies of the GSP and IOM samplers and the 37-mm closed-face cassette demonstrated a good match to the data measured by Kenny *et al.* (1997). Differences observed for the 37-mm cassette may be attributed to use of nonconductive polystyrene cassettes by Kenny *et al.* (1997) in contrast to our experiments. Further discussion of the accuracy, bias, and precision of the samplers is difficult because of the limited number of wind velocities and aerosol particle sizes involved in this study and is beyond the scope of this paper.

Direction-averaged versus direction-specific sampling efficiencies

The usefulness of the direction-specific approach to studying sampling efficiencies of personal inhalable aerosol samplers was mentioned in the introduction. Table 4 illustrates

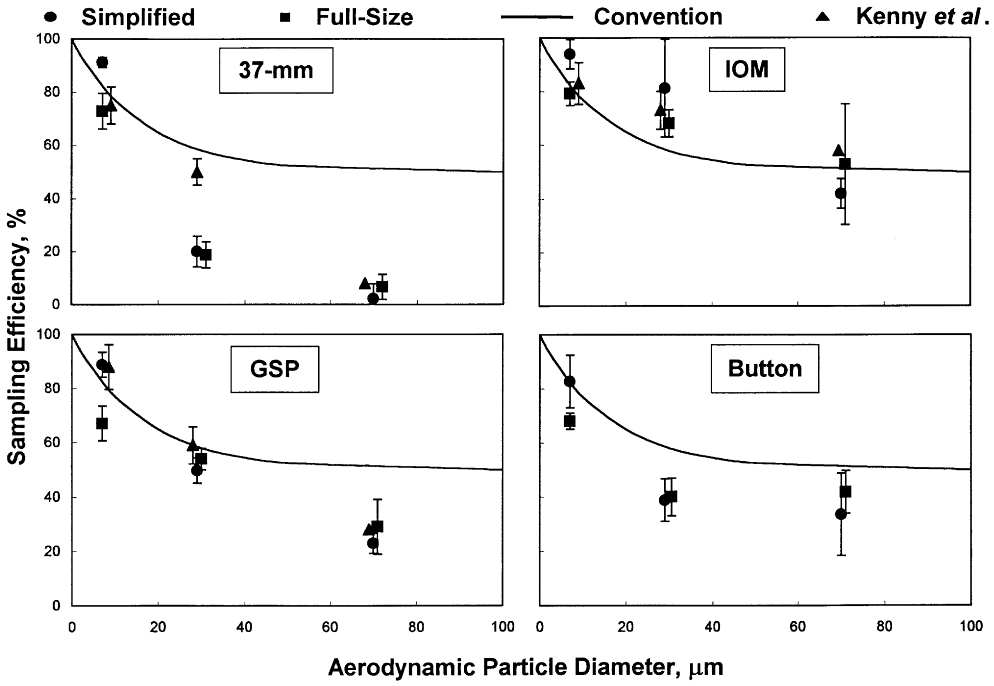

Fig. 3. Calculated direction-averaged sampling efficiencies of the four test samplers and data by Kenny *et al.* (1997). $U_w = 0.5 \text{ m s}^{-1}$.

Table 4. Direction-specific (at 0, 90, and 180° to the wind) and direction-averaged sampling efficiencies (%) of the IOM and GSP samplers mounted on the simplified torso and subjected to 70 μm aerosol particles*

Sampler	Wind velocity ($\mathrm{m\,s^{-1}}$)	0°	90°	180°	Direction-averaged
IOM	0.5	92.2 ± 9.5	10.2 ± 2.2	55 ± 2.5	41.9 ± 5.5
	2.0	344 ± 48	10.9 ± 7.1	41 ± 5.1	102 ± 3
GSP	0.5	46.7 ± 3.2	3.8 ± 1.7	37.3 ± 6.0	22.9 ± 3.7
	2.0	85.9 ± 15.0	6.3 ± 3.4	18.1 ± 5.5	29.0 ± 8.5

*According to the Inhalable Convention, sampling efficiency for 70 μm particles is 50.7%.

this on the example of the IOM and GSP samplers subjected to 70 μm aerosol at both 0.5 and 2.0 $\mathrm{m\,s^{-1}}$ wind velocities and mounted on the simplified torso. It presents direction-specific and direction-averaged aerosol sampling efficiencies and standard deviations of these two samplers. The former is based on the measured data and the latter was calculated. According to the inhalable convention (Inhalable Particulate Mass—TLV), the sampling efficiency of a personal inhalable aerosol sampler collecting particles with 70 μm aerodynamic diameter should be 50.7% regardless of the ambient wind velocity and direction (ACGIH, 1999). From examination of Table 4 we can note that the direction-averaged sampling efficiency presents a more reasonable match with the inhalable convention than most of the discrete orientations. While facing the wind, the IOM sampler oversamples by up to the factor of 7 compared to the targeted value of 50.7%. At the same time, it undersamples by a factor of 5 compared to the same value when oriented at 90° to the wind. From Table 4, the ratios of the highest to lowest direction-specific sampling efficiencies at $U_w = 2.0\ \mathrm{m\,s^{-1}}$ are about 31 and 14 for the IOM and GSP samplers, respectively. It is believed that the sampling efficiency of the IOM sampler is such a strong function of its orientation because of its large 15-mm diameter inlet, while the GSP sampler's extended inlet distance from the torso may produce a similar effect. The sampling efficiencies of the two other test samplers exhibited similar (though not as strong) patterns of dependence on the their sampling orientation. This additional information on sampler performance yielded by the simplified test protocol is a beneficial feature that cannot be retrieved when sampling is conducted on a continuously rotating manikin.

CONCLUSIONS

Simplification of costly and time-consuming procedures used for the performance evaluation of personal inhalable aerosol samplers recently became an area of interest. One of the alternative approaches, a simplified test protocol first presented by Witschger *et al.* (1998), was studied further in this paper. This protocol reduces the size of the manikin and standardizes the shape to a rectangular simplified torso with rounded edges measuring $33 \times 21 \times 21\ \mathrm{cm}^3$. These dimensions are typical of the middle part of a human torso. Also, the experimental procedure was changed from using a continuously rotating manikin technique to one sampling in four principal orientations simultaneously (0, 90, 180, and 270°).

The aerosol sampling efficiencies of the four personal inhalable aerosol samplers included in this study were investigated at several particle sizes and wind speeds. When the samplers were mounted on the simplified torso versus the full-size manikin, their sampling efficiencies were statistically not different from each other ($p = 0.26$). Also, the samplers demonstrated high correlation with respect to changing sampling conditions.

Use of a rotating manikin for testing inhalable samplers is a convention that has been developed to simulate human exposure. We developed a simplified torso that provides results agreeing well with the current conventional system, while it is better defined than commercial manikins that come in a wide variety of shapes and configurations. We have developed a test protocol based on this simplified torso that is simpler and provides additional orientation-specific information. We conclude that, if adopted as the conventional approach, the simplified test protocol would provide a sufficiently rigorous test of inhalable sampler performance at a potentially lower cost.

Acknowledgment—This study was partially supported by the National Institute for Occupational Safety and Health through Grant No. RO1-OH-03328. V.A. was also partially supported through the NIOSH ERC Grant No. T42 CCT-510420. The authors are thankful for this support.

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