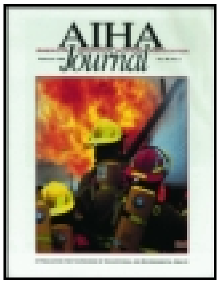

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Performance Characteristics of the Button Personal Inhalable Aerosol Sampler

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APPLIED STUDIES

Performance Characteristics of the Button Personal Inhalable Aerosol Sampler

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The button inhalable aerosol sampler with a curved porous inlet recently was developed and evaluated as a stationary sampler in the laboratory and in the field. The present study focused on investigating its suitability for personal inhalable aerosol sampling. The button sampler was tested at two wind velocities (0.5 and 2.0 m/sec), three particle sizes (7, 29, and 70 μm) and three orientations to the wind (0, 90, and 180°). The performance characteristics of the button sampler were compared with those of three other personal samplers—the IOM (Institute of Occupational Medicine), GSP, and 37-mm closed-face filter cassette. The experiments were conducted in a wind tunnel with the samplers mounted on a full-size manikin. The direction-specific sampling efficiency of the button sampler was found to be essentially independent of the wind direction and dependent on the wind velocity to a much smaller degree than that of the three other samplers. When direction-averaged, the fit of its sampling efficiency curve to the inhalability curve was found to be better than that of the 37-mm closed-face cassette, comparable with that of the GSP sampler, and less than that of the IOM sampler. The precision of the button sampler was found to be generally equal to or better than the precision of the comparison samplers. It was concluded that the button sampler can be successfully used as a personal inhalable aerosol sampler.

Keywords: inhalable aerosols, personal sampling, wind tunnel evaluation

Aerosol samplers are among the most important and widely used tools of modern industrial hygiene. Their designs depend on a wide variety of physical principles, such as filtration, inertial and gravitational collection, passive diffusion, thermophoresis, electrostatic effects, and so forth. Personal aerosol samplers, along with static samplers and direct-reading instruments, are widely used for the monitoring of workplace airborne particulate stressors and play an important role in ensuring the adequate protection of workers. Although personal aerosol samplers have been available for many years for the collection of the respirable particle size fraction, today the emphasis is on the development and refinement of personal aerosol samplers that are capable of capturing particles in a much wider inhalable size fraction.(1) A wide variety of personal inhalable aerosol samplers are currently in use in the United States and abroad. Some of them were developed decades ago, before the advent of the concepts of health-related aerosol fractions and particle size-selective sampling efficiencies. Since then considerable knowledge has been gained on inlet sampling efficiency and on how the incoming air and particle flows interact with the sampler and the bluff (human) body on which the sampler is mounted (see, e.g., theoretical studies by Ingham,(2) Ingham and Hildyard,(3) Vincent,(1) Tsai et al.,(4) and experimental studies by Kenny et al.(5) and Witschger et al.(6)) . The emergence of the ACGIH®/CEN EN 481/ISO 7708 (American Conference of Governmental Industrial Hygienists, Comité Européen de Normalisation, International Organization for Standardization) inhalable sampling convention(7–9) added to the sampler performance requirements, based on the current advances in aerosol science (respirable and thoracic sampling conventions were also specified in the above documents). Different commercially available personal inhalable (as well as respirable and thoracic)

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samplers meet these requirements with varying degrees of success.

For instance, the 37-mm closed-face filter cassette, the most common personal aerosol sampler in the United States, found its initial aerosol application approximately 30 years ago in sampling total particulates, with no regard for the inhalable aerosol fraction.(10) Several researchers have shown that its aerosol sampling efficiency falls short of the above inhalable sampling convention (e.g., Buchan et al.(11)) . This difference is especially pronounced for particle sizes higher than 20 μm.(5)

The limited compliance of the currently used particle size-selective personal aerosol sampling methods with the inhalable convention is caused by a host of factors that exert their influence during particle aspiration into an inlet and aerosol transport through the sampling line.(12–14) These factors include electrostatically induced biases; temperature- and humidity-induced changes in filter weight and deterioration (loss) of sample with time (that affect filter and sample stability, respectively); internal particle losses; and dependence of the sampling efficiency on wind velocity and orientation of the inlet with respect to the wind. Fairchild et al.(15) found that the closed-face 37-mm cassette undersamples relative to the ambient aerosol concentration when it is oriented away from a horizontal aerosol flow, whereas it oversamples by as much as 100% when it faces the wind. Beaulieu et al.(16) came to similar conclusions for the closed-face cassette operating in calm air. This dependence of the sampling efficiency on the sampler's orientation becomes an issue in the frequently encountered situation in which a worker maintains a relatively constant orientation with respect to the source of the contaminant. In such a situation, sampling bias is likely, resulting in significant over- or underestimation of the worker's exposure. Aizenberg et al.(17) found that the IOM (Institute of Occupational Medicine) sampler facing the wind may overestimate the ambient concentration of 70 μm particles by as much as 270% at a wind velocity of 2 m/sec. When the IOM sampler is oriented at 180° to the wind, its sampling efficiency was found to be only 30% for the same sampling conditions (40% for 90° orientation). Vincent(1) discussed the strong wind velocity dependence of the sampling efficiency of several of the most popular personal samplers. Kenny et al.(5) demonstrated that the direction-averaged sampling efficiency of a number of personal inhalable aerosol samplers may vary by a factor of up to four (depending on the particle size) at typical indoor and outdoor wind conditions.

The airflow character is also an important consideration: Wiener et al.(18) showed that when the air turbulence of 7.5% intensity is introduced (i.e., the random fluctuations of the air flow constitute 7.5% of the mean flow), the sampling efficiency of a sharp-edged isokinetic sampler varies by a factor of up to two (at the same inlet velocity) for high-inertia 30 μm particles that cannot follow airflow streamlines closely. Vincent(1) noted that the air turbulence causes variabilities in the aspiration efficiency of blunt aerosol samplers that may be greater than those that are due to the analytical procedure alone. Okazaki et al.(19) found that for nonisoaxial sampling with the inlet oriented in the vertical plane, losses due to impaction on the inner surface may also be significant.

Workplace aerosols can often contain very large particles with aerodynamic diameters exceeding 100 μm.(20,21) Aitken and Donaldson(20) found that the aspiration efficiency of a breathing manikin—while sampling 300 μm particles—was 12%, while that of the IOM sampler was found to be 155%. Thus, considerable oversampling occurs in this situation. Attempts to outfit personal inhalable aerosol samplers with inlet shields of various designs have been only partially successful (e.g., Sylvain(21)).

Ogden and Birkett(22) proposed that the sampling efficiency of an inhalable sampler should essentially be independent of wind direction and velocity, and exhibit only low dependence with respect to particle size. Although these criteria were suggested for static inhalable samplers (e.g., for their overall respirable burden [ORB] sampler), they should be extended to personal inhalable samplers.

To summarize, a successful modern personal inhalable aerosol sampler should possess the following features and performance characteristics. Its sampling efficiency should closely simulate the ACGIH/CEN/ISO inhalable convention and demonstrate low dependence on wind velocity and direction (both in the horizontal and vertical planes). Particle transmission losses should be minimized. The sampler should not induce significant turbulence in the vicinity of its inlet, thus avoiding altering the incoming airflow field. The undesirable effects associated with electrical charge accumulation on its surface should be eliminated or minimized by, for example, using conductive material. Particle deposition on the collection filter should be close-to-uniform to improve the accuracy of various analytical methods (e.g., field-portable X-ray fluorescence, fiber counting, enumeration of bioaerosol particles, etc.). The problem of oversampling particles with diameters exceeding 100 μm should be addressed. It should be noted that this list is not complete. The most important of these criteria, such as match to the inhalable convention and low dependence on the ambient wind conditions, may be hard to implement simultaneously for personal inhalable aerosol sampling.

BUTTON PERSONAL INHALABLE AEROSOL SAMPLER

Sampler Design

A small aerosol sampler with a curved porous inlet surface has been developed.(23,24) It is referred to as the button sampler and is now commercially available from SKC Inc. (Eighty Four, Pa). The button sampler is schematically shown in Figure 1. Its inlet is formed by a portion of a spherical shell with numerous, identical, evenly spaced orifices. The particles are collected on a 25-mm filter, placed directly behind the inlet. The button sampler evaluated in this study has an inlet porosity of 21%, with orifices that are 381 μm in diameter. The inlet screen has a subtended angle of 160°, which results in an inlet screen area of 19.6 cm^2. The sampling flow rate of 4 L/min results in a sufficient pressure drop to enhance the uniformity of the deposition on the filter (most conventional filter materials can be used). Several commercially available personal pumps are capable of sustaining this flow rate for periods of several hours. The body of the button sampler can be machined of aluminum or molded in conductive plastic (aluminum samplers were used in this study). The screen was made of stainless steel to enhance the sampler's ruggedness.

The specific design criteria discussed above were taken into account in the design of the button sampler, as follows.

(1) The curved symmetrical geometry of the inlet reduces the effects of wind velocity and direction on sampling efficiency (in both vertical and horizontal planes) and improves filter deposit uniformity. This will be discussed in more detail in the Results and Discussion section.

(2) The blunt spherical shape of the inlet reduces turbulent effects induced by the flow separation, thus attenuating airflow disturbances near the inlet.

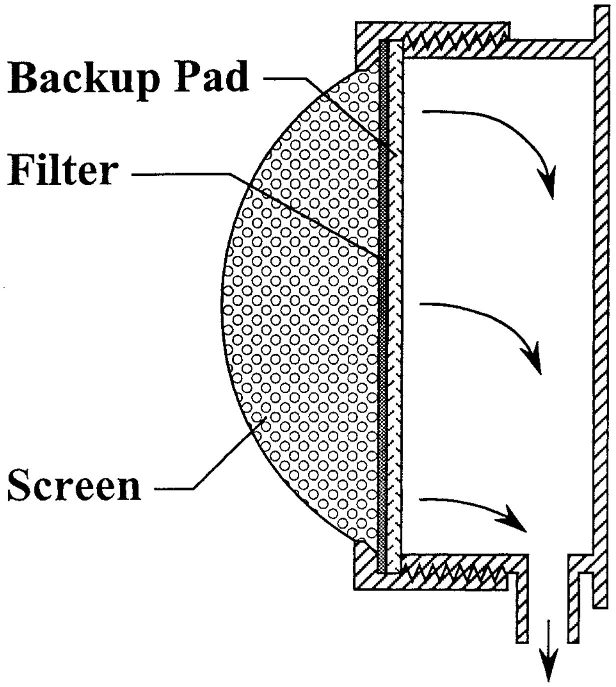

FIGURE 1. Schematic of button personal inhalable aerosol sampler

(3) Placing the filter directly behind the inlet reduces transmission losses.
(4) The sampler has reduced susceptibility to electrostatic effects because it is made of either metal or conductive plastic.

In addition, the inlet screen of the button sampler has an advantage in environments where large particles are present, e.g., in abrasive blasting and woodworking, because its screen significantly reduces the sampling of the particles with sizes beyond the established inhalability range (above 100 μm). Based on Aitken and Donaldson(20) data, it is thought that this allows the button sampler to more closely simulate the human inhalability characteristics in the range of very large particles. The partially spherical meshlike inlet of the button sampler resembles the cylindrically shaped mesh screen that Aitken and Donaldson(20) found to be advantageous in reducing oversampling of very large particles by the IOM sampler. Although the screen is not the main subject of the present study, it is an important feature of the button sampler.

Previous Studies

The first prototype of the button sampler was evaluated in a 400 cm² cross-section wind tunnel as a freely suspended (stationary) sampler at flow rates ranging from 2 to 5 L/min.(24) Several wind velocities and inlet designs (porosities and orifice diameters) were used. The button sampler also was evaluated as a stationary sampler in residential settings during environmental clean-up while being operated at a flow rate of 10 L/min.(25) The sampling efficiency was found to have low sensitivity to wind velocity in both studies, and the particle deposition on the sampler's collection surface was nearly uniform. The study by Hauck et al.(25) also indicated low intersample variability of the button sampler, as well as the possibility of using it for stationary bioaerosol monitoring (fungal spores).

In a more recent airflow study,(26) the button sampler prototype was tested while being freely suspended and attached to a small stagnation plate simulating the human torso. The limiting streamlines near the button sampler inlet were determined using both the theoretical and experimental approaches. The blunt inlet of the button sampler was shown not to significantly affect the incoming airflow at typical indoor and outdoor wind velocities. Little effect of the plate on the airflow and particle trajectory profiles was observed near the inlet facing the wind. Thus, the results of that study suggest that the button sampler is also suitable for personal aerosol sampling. The present study was initiated to verify this hypothesis. The sampling efficiency of the button personal sampler mounted on a full-size manikin in a large cross-section wind tunnel was investigated with respect to the inhalable convention.

EXPERIMENTAL DESIGN

A schematic diagram of the experimental setup is presented in Figure 2. It is similar to the setup used by Witschger et al.(9) and Aizenberg et al.(17) The experiments were carried out in a large cross-section (122 cm high × 183 cm wide ≈ 22,300 cm²) wind tunnel located at the National Institute for Occupational Safety and Health in Cincinnati, Ohio. A honeycomb was installed as a flow straightener approximately 0.6 m upstream of the aerosol injection nozzle, thus ensuring close to laminar airflow: The air velocity in the test section was uniform to within ±5%, and the turbulence intensity was less than 6% at 1.6 m from the honeycomb for the air velocity range of 0.5 to 2 m/sec,(9) which is in line with Baines and Peterson's(27) theoretical prediction. The uniformity of aerosol concentration in the test area was achieved by mounting the injection nozzle on a scanning system traversing a 66 cm high × 127 cm wide section of the wind tunnel. These arrangements resulted in a stable aerosol concentration and uniform airflow throughout the cross section of the wind tunnel. Thus, adequate repeatability of results within and between experiments could be ensured.

Three traverses over a period of 2.5 hours were made per experiment. The uniformity of the particle concentration was determined for each particle size tested using 10 isokinetic samplers positioned in such a way as to cover most of the test area cross section. The coefficients of variation of the measured concentrations were typically below 10%.(17)

Aluminum oxide (alumina) particles, CAS# 1344–28–1, (Fusco Abrasive Systems Inc., Compton, Calif.) were used as test aerosols. The aerosol was generated by a rotating 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 bipolar ions produced by an airflow controller (model AFC-2, Richmond Static Control Services Inc., Palm Springs, Calif.). A sedigraph (model 5000, Micromeritics Instrument Corp., Norcross, Ga.) was used to obtain a series of log-normal cumulative plots of the alumina particle size distributions prior to the beginning of this study. Mass median aerodynamic diameters were calculated using these plots following a procedure described by Mark et al.(28) Geometric standard deviations were also yielded by these plots. Six identical button samplers were mounted on a full-size tailor's manikin (three on the front, three on the back). The particles aspired into each sampler were collected on 25-mm glass-fiber filters (Gelman Instrument Company, Ann Arbor, Mich.). Since these filters are susceptible to changes in temperature and humidity, they were equilibrated before and after each test in a

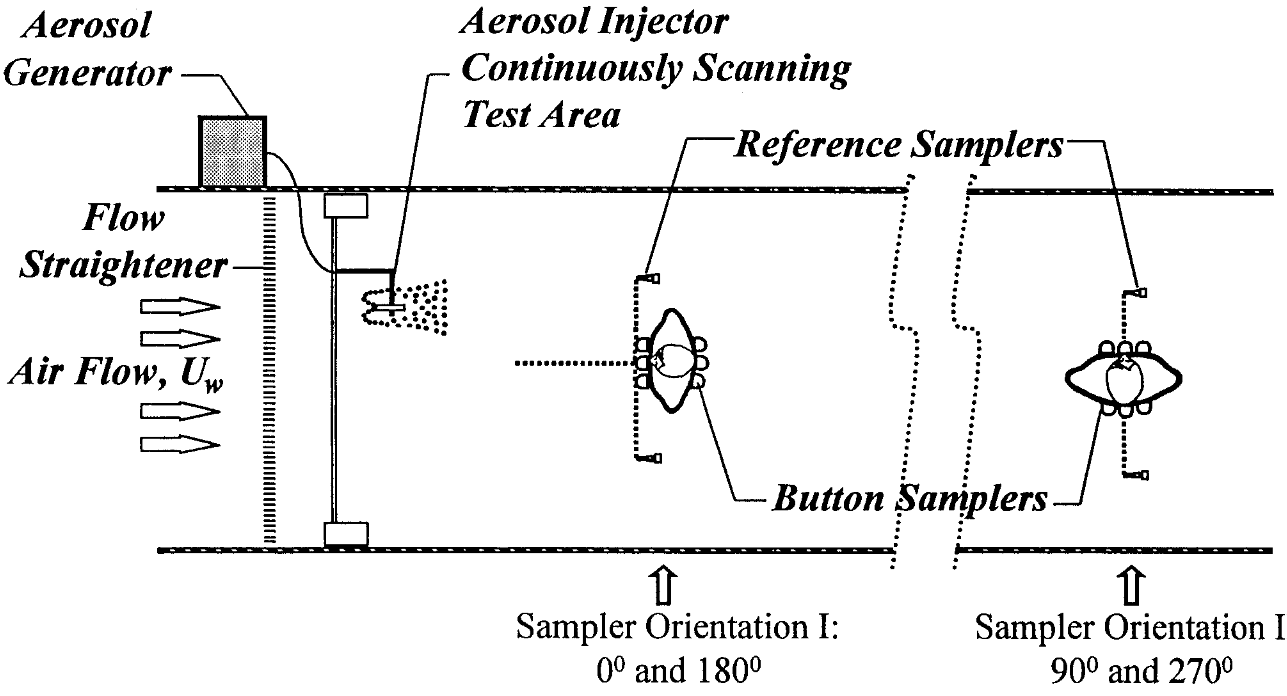

FIGURE 2. Experimental setup

climate-controlled room (24±2°C, RH 55 ±3%) for at least 4 hours. No electrostatic effects associated with the glass-fiber filter material were encountered. The mass collected on each filter was determined by gravimetric analysis using an analytical balance (model AT20, Mettler Toledo Inc., Hightstown, N.J.). The limits of detection and quantitation were 64 and 214 μg per sample, respectively (similar to those indicated in Witschger et al.(9)).

The manikin with the samplers was placed in the test area of the wind tunnel facing the incoming airflow (Orientation I) or at 90° to it (Orientation II), as shown in Figure 2. Aerosol was injected into the test area approximately 1 m upstream of the torso in the direction opposite to the airflow. This arrangement reduced the probability of projecting particle agglomerates directly into the sampler inlets.

There were three independent experimental variables in this study: particle size, wind velocity, and sampling orientation. Three aerosols with mass median aerodynamic diameters of 7, 29, and 70 μm were used for these tests (the geometric standard deviation was about 1.35 for each size). These aerosols were representative of the lower, intermediate, and upper parts of the inhalable fraction. The tests were conducted at two wind velocities (U_w), 0.5 and 2.0 m/sec, which represent indoor and outdoor occupational environments, respectively. This study's hypothesis regarding the wind velocity was that the relationship between the button sampler's sampling efficiency and wind velocity is not significant at the 95% significance level. Three sampling orientations were involved in this study: 0, 90, and 180° (90 and 270° orientations were treated as identical based on the considerations of symmetry). The 0 and 180° orientations were tested simultaneously (see Figure 2). In contrast to traditional techniques that involve slow rotation of the manikin, no such procedure was used in this study. The authors believe that the three "principal" orientations involved in this study are of the most interest in aerosol sampling because they represent the three main sampling situations: when the entire inlet area is facing the wind (0°), when the smallest projected area of the inlet is facing the wind (90 or 270°), and when the sampling is conducted from the turbulent wake of the body (180°). Also, they comprise the minimum set of values necessary to construct a weighted sum for calculating the direction-averaged sampling efficiency of a sampler if such is required. When the sampling orientations were studied, the hypothesis was that the orientation does not significantly affect the sampling efficiency of the button sampler. The significance level of 95% (i.e., the 95% probability of not rejecting the study hypotheses when they are true) was maintained.

Three other models of personal aerosol samplers, namely the GSP (Gesamtstaub-Probenahmesystem), IOM, and the 37-mm closed face cassette made of conductive plastic, were selected from a wide variety of commercially available devices used in today's practice of personal sampling for inhalable and total aerosols and included in this study for comparison. As shown in Figure 2, a total of six samplers (either all button samplers or two of each three comparison samplers) were mounted on the front and the back of the manikin in each test.

The actual aerosol concentration in the wind tunnel was kept as close to constant as possible during all experiments by controlling the aerosol generation rate. Concentration was determined using reference isokinetic samplers (two per experiment) shown in Figure 2. The samplers were placed symmetrically on each side of the manikin at a distance of at least 20 cm. Witschger et al.(9) have shown that at this distance the airflow is not significantly disturbed by the presence of the manikin. The isokinetic samplers operated at flow rates of 2.5 and 10 L/min (at wind velocities of 0.5 and 2.0 m/sec, respectively). A high-volume pump supplied the vacuum needed to create these flow rates through the 2.5 and 10 L/min critical orifices. The 4 L/min flows through the button samplers were achieved in a similar way.

The direction-specific sampling efficiency of the button sampler

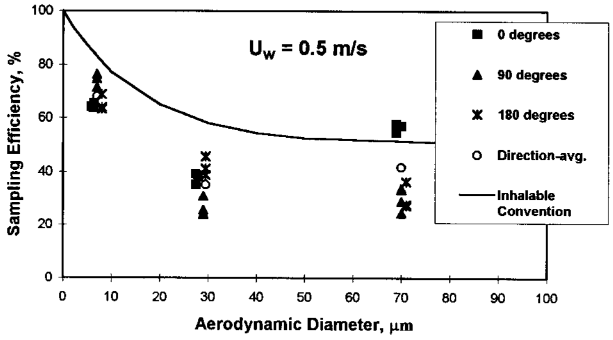

FIGURE 3. Direction-average and direction-specific sampling efficiencies of the button sampler

TABLE I. CV of the Sampling Efficiency of Four Samplers at Different Sampling Orientations and Particle Sizes; U_w = 0.5 m/sec

Orientation of Sampler to the Wind	Sampler	CV, % Particle Aerodynamic Diameter, μm 7	29	70
0°	button	1.4	5.4	2.9
	GSP	3.8	2.7	12.2
	IOM	6.1	1.4	10.7
	37-mm	5.9	33.1	35.5
90°	button	4.6	12.5	8.8
	GSP	3.9	8.9	19.7
	IOM	5.6	31.0	35.3
	37-mm	5.9	11.2	57.3
180°	button	4.6	8.5	16.8
	GSP	13.9	5.4	30.1
	IOM	4.0	1.5	2.7
	37-mm	2.8	21.3	17.8

was determined as the ratio of the aerosol concentration measured by the button sampler to the average aerosol concentration measured by the two reference samplers during the same experiment. The direction-averaged sampling efficiency, $E_{dir\text{-}avg}$, was calculated from the sampling efficiencies measured at the three discrete orientations, E_0, E_{90}, and E_{180}:

$$E_{dir\text{-}avg} = \tfrac{1}{4}\,(E_0 + 2\,E_{90} + E_{180}) \qquad \textbf{(1)}$$

Equation 1 reflects the fact that, in a continuous rotation mode, a sampler is oriented at 0 and 180° to the wind only once per full rotation, whereas it is twice oriented at 90° to the wind (i.e., at 90 and 270°). This weighted average represents the relative time contributions of each of the discrete orientations and is the simplest approach for calculating $E_{dir\text{-}avg}$. While not as rigorously justified as Tsai et al.'s(4) approach, Equation 1 allows quick and adequate estimation of the direction-averaged sampling efficiency. Equation 1 can be modified if other weights are applied. These weights may reflect different relative time contributions to the direction-averaged sampling efficiency. Also, the measurement of more discrete sampling efficiencies might yield a more accurate direction-averaged sampling efficiency. Further studies of this matter are needed.

All tests 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 the unbalanced design (i.e., when unequal number of repeats is assigned to each combination of experimental variables) were implemented.

RESULTS AND DISCUSSION

Direction-Specific and Direction-Averaged Sampling Efficiencies of the Button Sampler

Figure 3 presents the sampling efficiency of the button sampler measured in three principal orientations (0, 90, and 180°) for all three particle sizes at U_w = 0.5 m/sec. Each data point at 0 and 180° represents the average sampling efficiency measured in the same experiment by three samplers, and all data points at 90° are the averages of the sampling efficiencies of six samplers from the same experiment (within-experiment coefficients of variation ranged between 2% for 7 μm particles and 10% for 70 μm particles). Each data point presented in Figure 3 represents an average of one experiment. No averaging over all repeats was performed to better reflect the repeatability of results yielded by the button sampler (i.e., its precision). The direction-averaged sampling efficiency of the button sampler calculated from these data is presented in the same figure. Figure 3 also shows the ACGIH/CEN/ISO inhalable convention curve.(7)

One-way analyses of variance (ANOVA) for each particle size were conducted on the data presented in Figure 3 to test the hypothesis that orientation does not significantly affect the sampling efficiency of the button sampler (at the 95% significance level). It was found that the sampling efficiency of the button sampler measured at specific sampling orientations ranging from 0 to 180° did not depend significantly on these orientations. This result was reached after differences in the sampling efficiency associated with repetitions were accounted for (pooled with the error) and the variations due to the different orientations were found not be statistically significant (p-values were 0.09, 0.072, and 0.051 for the particle sizes of 7, 29, and 70 μm, respectively). A similar conclusion was reached regarding wind velocity of U_w = 2.0 m/sec (p-values ranged from 0.049 to 0.059). It should be noted, however, that these tests were not very powerful due to the low number of error degrees of freedom (i.e., the differences in the sampling efficiency must be large for the test to detect them).

To further support the result of this subsection, the precision of all four samplers was evaluated using the sampling efficiency data obtained at the discrete orientations. The coefficients of variation (CV) of the sampling efficiency, which characterize the precision possessed by each sampler, were calculated using nine data points yielded by the button samplers (three button samplers per test times three repeats) and six data points yielded by each of the three other samplers (two comparison samplers per test times three repeats) for each combination of the wind velocity and particle size. The results are presented in Table I (for U_w = 0.5 m/sec). It can be seen that for most of the tested situations the CV of the button sampler did not exceed 10%. Table I also shows that in most sampling situations, the button sampler demonstrated the best or second-best precision among the four tested samplers in all sampling orientations. Its CV exceeded 10% only twice: at 90°/29 μm and 180°/70 μm. This underscores the above-mentioned feature of the button sampler—the low sensitivity of its efficiency to the wind direction. The direction-specific data on the sampling efficiency of the button sampler obtained for U_w = 2.0 m/sec demonstrated trends similar to those obtained at U_w = 0.5 m/sec and presented in Figure 3 and Table I. The CVs determined

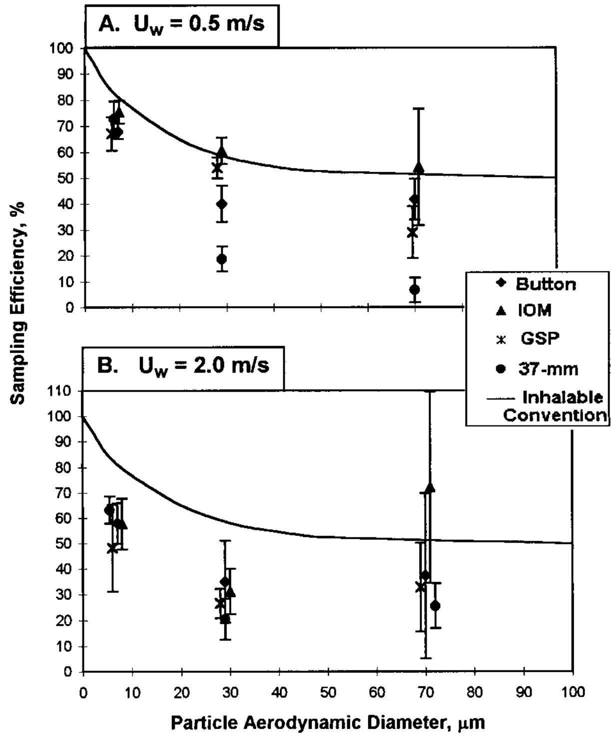

FIGURE 4. Direction-averaged sampling efficiencies of four samplers. (A) $U_w = 0.5$ m/sec. (B) $U_w = 2.0$ m/sec.

for the button sampler at $U_w = 2.0$ m/sec ranged from 1.48 (7 μm, 90°) to 23.9 (70 μm, 180°).

Comparison of Direction-Averaged Sampling Efficiencies of Four Samplers

This section presents a comparison of the direction-averaged sampling efficiency data of the button sampler with those of its peers (the IOM, GSP, and 37-mm closed-face cassette). The calculated direction-averaged sampling efficiency values of the four samplers and the ACGIH/CEN/ISO inhalability curve are shown in Figure 4. Values for the four samplers were derived from the direction-specific values using Equation 1. The values in Figure 4 are plotted for all three particle sizes (7, 29, and 70 μm) and both wind velocities (0.5 and 2.0 m/sec). The error bars represent the standard deviations that were also calculated from the direction-specific standard deviations of the sampling efficiency data for each sampler operated in the three principal orientations. All values presented in Figure 4 are averages of at least three tests.

The direction-averaged sampling efficiencies and the corresponding variances exhibited by the three comparison samplers at $U_w = 0.5$ m/sec follow closely the data reported by Kenny et al.,(5) Vincent,(1) and Buchan et al.(11) for these samplers tested using a rotating manikin (e.g., the difference between Kenny et al.'s and the present data was typically about 7%). This fact supports the direction-averaging procedure employed in this study and described by Equation 1.

At $U_w = 0.5$ m/sec, the direction-averaged sampling efficiency of the button sampler was found to fit the inhalable convention significantly better than that of the 37-mm filter cassette. The data yielded by the GSP sampler is comparable with those of the button sampler. The direction-averaged sampling efficiency data of the IOM sampler are closest to the inhalability curve. For $U_w = 2$ m/sec, the differences are not as pronounced as for 0.5 m/sec. For larger particles, though, the button and the IOM samplers' data match the convention better than those of the two other samplers. None of the four samplers, however, showed a perfect match with the inhalability curve. At the same time, the button sampler was found to be the least dependent on changes in U_w: Two-way ANOVA demonstrated that the change in U_w had a statistically weak effect on the change in the direction-averaged sampling efficiency of the button sampler. Weights equal to the reciprocal of the respective variances were used in this analysis because they present the unbiased least square estimates of the "true" values.(29) This analysis yielded a p-value that falls in the transitional region between statistically significant and not significant results ($p=0.0485$). The significance of interaction between U_w and particle size also fell in this region ($p=0.046$). Similar analysis for the other three samplers showed very strong dependence of their sampling efficiency on U_w ($p<0.0001$). The p-value for the button sampler is about 500 times higher than that of any of the comparison samplers. Thus, the button sampler is about 500 times more likely not to respond to the wind velocity changes than any of the comparison samplers. From this it is concluded that the sampling efficiency of the button sampler depends less on U_w than does that of the GSP, IOM, and 37-mm cassette.

CONCLUSIONS

The button inhalable aerosol sampler, which in earlier studies was found to be suitable for area (static) sampling, was investigated to determine its suitability for personal sampling. The following performance characteristics of the button sampler were found.

- The sampling efficiency of the button sampler was found not to depend significantly (at 95% significance level) on its orientation to the wind (i.e., wind direction). This finding is especially notable at the wind velocity of 0.5 m/sec (p-values ranged from 0.051 to 0.09).
- When compared with three other commonly used personal aerosol samplers, the direction-averaged sampling efficiency of the button sampler follows the inhalability convention better than that of the 37-mm closed-face cassette. The fit of the GSP sampler data is comparable with that of the button sampler. The IOM sampler data are the closest to the inhalability curve.
- The sampling efficiency of the button sampler exhibited lower dependence on wind velocity than did the sampling efficiencies of the three comparison samplers.
- The precision of the button sampler, when expressed in terms of the CVs, was found to be equal to or better than the precision of the comparison samplers.

None of the four samplers involved in this study demonstrated a perfect match with the inhalable convention. At best, the match was fair, as in the cases of the button and IOM samplers. The 37-mm cassette, which is the most commonly used industrial hygiene sampler, demonstrated the poorest fit to the inhalable convention. The button sampler was found to possess features such as good precision and low sensitivity to wind direction and velocity that are not found in its peers.

Considering the button sampler's accuracy and precision when mounted on a manikin, it is concluded that the button sampler is useful as a personal inhalable aerosol sampler when operated at a flow rate of 4 L/min. The button sampler is believed to be especially valuable for aerosol monitoring in workplaces where frequent changes in wind direction and velocity are anticipated.

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