

A Rotating Bluff-Body Disc for Reduced Variability in Wind Tunnel Aerosol Studies

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A rotating bluff-body disc (RBD) was developed to reduce spatiotemporal variability associated with sampling supermicron aerosol in low-velocity wind tunnels. The RBD is designed to rotate eight personal aerosol samplers around a circular path in a forward-facing plane aligned with the wind tunnel cross section. Rotation of the RBD allows each sampler to traverse an identical path about the wind tunnel cross section, which reduces the effects of spatial heterogeneity associated with dispersing supermicron aerosol in low-velocity wind tunnels. Samplers are positioned on the face of the RBD via sampling ports, which connect to an air manifold on the back of the disc. Flow through each sampler was controlled with a critical orifice or needle valve, allowing air to be drawn through the manifold with a single pump. A metal tube, attached to this manifold, serves as both the axis of rotation and the flow conduction path (between the samplers and the vacuum source). Validation of the RBD was performed with isokinetic samplers and 37-mm cassettes. For facing-the-wind tests, the rotation of the RBD significantly decreased intra-sampler variability when challenged with particle diameters from 1 to 100 μm . The RBD was then employed to determine the aspiration efficiency of Institute of Occupational Medicine (IOM) personal samplers under a facing-the-wind condition. Operation of IOM samplers on the RBD reduced the between-sampler variability for all particle sizes tested.

Keywords: aerosol sampling; IOM sampler; wind tunnel

INTRODUCTION

Aspiration efficiency studies of personal aerosol samplers are often conducted within a wind tunnel where a test aerosol, dispersed upstream of the samplers, is carried into the test section by virtue of the airflow. However, these tests are often complicated by inhomogeneities in the aerosol concentration across time and space, especially when evaluating inter-sampler and intra-sampler aspiration efficiencies. Such inhomogeneities can lead to random error, which reduces the

power of statistical comparisons, and systematic error, which can lead to bias. These errors are particularly evident when large particles (aerodynamic diameter, $d_{ae} > 25 \mu\text{m}$) are studied, as these particles have substantial settling velocities and are difficult to disperse uniformly throughout a wind tunnel cross section (Ramachandran *et al.*, 1998). One field of study requiring uniform concentrations of large particles in wind tunnels is that of inhalable aerosol sampling. Because the convention for inhalable particles extends to aerodynamic diameters up to 100 μm , experimental evaluation of personal inhalable aerosol samplers must include large particles to ensure that physiologically relevant exposures may be monitored.

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Many researchers have highlighted the difficulties associated with achieving temporally and spatially homogeneous distributions of supermicron aerosol in wind tunnels (e.g. Liden and Kenny 1994; Aizenberg *et al.* 2001). As a result, a number of studies have focused on minimizing these inhomogeneities. Some studies have focused on engineering the aerosol generation system to improve homogeneity. For example, Smith *et al.* (1999) developed a complex aerosol generation system in which the aerosol generator was moved about a predefined grid to establish concentration uniformity (10% relative standard deviation or better) for particles between 7 and 70 μm . A similar system was employed by Schmees *et al.* (2008). Heist *et al.* (2003) described the design of an array of compressed air-driven venturi nozzles that dispersed solid particles from a conveyor belt and gravity-fed hopper. This system produced a spatially uniform concentration for low wind speeds; relative SD <7% at 1.0 m s^{-1} and <5% at 0.1 m s^{-1} for polydisperse aerosol with count median aerodynamic diameter of 5.4 μm and geometric SD of 2.4. Blackford and Heighington (1986) developed a recirculating wind tunnel that achieved constant dust concentrations within 7% in time and 3% in space. Thorpe and Walsh (2002) later evaluated this wind tunnel and found that the maximum variation was $\pm 3\%$ from its mean value in the range of 0–35 mg m^{-3} for particles 4–17 μm , when operating with a wind velocity of 0.5 and 2 m s^{-1} . While this method used less dust and gave greater control of the dust concentration than by constantly supplying dust to clean air, recirculating wind tunnels require large areas and may still be unable to provide uniform concentrations as particle sizes increase, particularly at velocities below those studied. Neither Heist *et al.* (2003) nor Thorpe and Walsh (2002), however, examined the variability associated with larger particles, which are more difficult to disperse homogeneously, yet necessary for evaluating the inhalability criterion.

Other research has focused on varying sampler location in the wind tunnel or sampler orientation relative to the aerosol flow. Aizenberg *et al.* (2001), for example, developed a system that moved both the aerosol generation system and the manikin holding the samplers relative to one another. Witschger *et al.* (2004) suggested that in nearly calm air, samplers could be placed in a circle surrounding a rotating aerosol generator at the center to challenge a set of samplers with similar aerosol concentrations. This technique allowed for 15 samplers to be evaluated simultaneously in a large aerosol chamber. To determine the reference concentration, they cited previous

research suggesting that sharp-edged/thin-walled probes could operate with nearly 100% aspiration efficiency when the Stokes number and sedimentation factors (the ratio of the settling velocity to the sampling velocity) are both much less than unity. This method produced highly uniform aerosol concentrations, with <12% relative standard deviations among samplers for particles with aerodynamic diameter between (d_{ac}) 6.9 and 76 μm . However, this method cannot be applied in a wind tunnel for which nonzero wind velocities are desired, as even small velocities would bias the mass collected by the samplers.

Marple and Rubow (1983) developed a small vertically oriented chamber (1.1 m^2 test area), designed to direct aerosol downward at low velocity (0.1–0.5 cm s^{-1}) toward a horizontally oriented turntable. Samplers mounted on the top face of the turntable were then rotated (0.25–2.1 r.p.m.) about the flow axis to account for spatial variations in the aerosol flow. For monodisperse particles with diameters between 2.5 and 15 μm , measured aerosol concentrations between replicate samplers generally varied by less than $\pm 3\%$, even when the turntable was not operated. When using polydisperse dust samples with diameters up to 20 μm , Marple and Rubow (1983) found that turntable operation improved concentration stability from $\pm 4.3\%$ with stationary samplers to $\pm 1.5\%$ with rotating samplers. The applicability of such a design at higher wind velocities or for use with larger particle diameters is uncertain, but the vertical orientation of this system precludes the study of gravitational effects on aspiration efficiency. However, these prior studies clearly demonstrate the benefit of rotating samplers about an identical path to reduce the unwanted effects of aerosol variations in space and time.

Based on the above systems, we have designed, constructed, and evaluated a rotating bluff-body disc (RBD) to account for spatial variations in aerosol concentration during wind tunnel testing of personal aerosol samplers. The motion of the RBD was such that each sampler traversed an identical path about the cross section of a horizontally oriented wind tunnel. We hypothesized that samplers mounted on the RBD would experience less intra-sampler variability as compared to samplers positioned at fixed locations about the wind tunnel cross section. The RBD is similar to a device discussed by D'Arcy *et al.* (1995); the research described here represents the first systematic evaluation of such a design. To evaluate the effectiveness of the RBD in reducing measured intra-sampler variability in the wind tunnel, eight samplers were placed on and adjacent to the RBD. Aerosol concentrations were compared among the samplers,

operating under both fixed and rotating conditions and challenged with multiple aerosols types and sizes.

DEVELOPMENT OF THE RBD

A schematic of the RBD is presented in Fig. 1. The RBD was comprised of a 40-cm diameter aluminum disc with eight sampling ports positioned equidistant about its outer edge. The eight sampling ports were chosen to minimize the influence of one samplers' vacuum on the flow path of another. The upstream cross-sectional area of air to be sampled through a port is directly proportional to the cross-sectional area of the inlet and the velocity of air through the inlet and inversely proportional to the wind velocity (Vincent *et al.*, 1986). For flow rates likely to be used in personal sampling ($\leq 10 \text{ l min}^{-1}$), and wind velocities $> 0.25 \text{ m s}^{-1}$, the distance between the samplers is at least four times larger than the diameter of this circular upstream sampled area. Personal and isokinetic samplers were connected to the front face of the aluminum disc using a through-wall fitting that directed sampler flow through the disc and into a central manifold at the rear face. Flow through each sampling port was regulated by either a critical orifice or a needle valve mounted on the back of the RBD. The manifold was connected to an aluminum tube (2.5-cm diameter \times 45-cm length) that served simultaneously as the axis of rotation and as a conduit for airflow. In this way, all eight samplers could be accommodated by a single pump while flow through each sampler was metered independently.

A chain and sprocket assembly connected the RBD tube to a gear motor, which was regulated with an adjustable speed controller. The gear motor and air pump were located outside and below the wind tunnel, preventing their exposure to test aerosols and eliminating their effects on airflow in the test section. A swivel fitting was connected to the rear end of the aluminum tube, allowing the tube and disc assembly to rotate

without twisting the airline to the pump. The RBD was rotated at 2–2.5 r.p.m., resulting in 120–150 revolutions of the eight samplers around the central cross section of the wind tunnel over a typical 60-min test.

Although wind tunnel aspiration efficiency studies are commonly conducted using a manikin to simulate anthropomorphic conditions, Kennedy *et al.* (2001) found that the use of a simple bluff body was sufficient. Similar results were found by Aizenberg *et al.* (2000). Paik and Vincent (2004) determined the aspiration efficiency as a function of Stokes number, velocity ratio (freestream velocity to velocity at sampler inlet), and dimension ratio (inlet diameter to bluff-body diameter) for wind tunnel studies. Their results suggested that aspiration efficiency was more sensitive to the Stokes number and velocity ratio than the dimension ratio. Their results suggest that the use of even bluff bodies may not be necessary to test aerosol samplers. These studies concluded that personal samplers could be tested without the use of full-size manikin. As such, it is possible to determine sampling efficiencies for a larger number of samplers during a single test. In the current study, the RBD provided a simple bluff body expected to give representative results for testing personal samplers.

VALIDATION AND PERFORMANCE EVALUATION OF THE RBD

All experiments were performed in a horizontal wind tunnel (1 \times 1 m in cross section, 3.5-m length, Fig. 2). Air entering the tunnel was first drawn through high efficiency particulate air (HEPA) filters using a five horsepower backward-curved airfoil fan. Air velocity through the tunnel was maintained at 0.4 m s^{-1} , set with a variable speed controller for the fan motor. A second set of HEPA filters, located at the rear of the tunnel, removed all test aerosol prior to reaching the fan and exhaust. Aerosol was injected into the tunnel through an opening in the

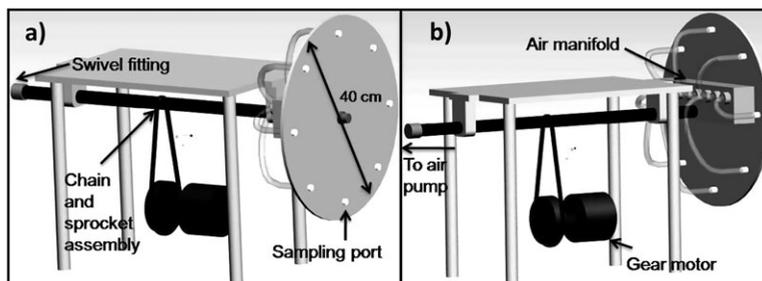


Fig. 1. Schematic of the RBD. (a) front view and b) rear view.

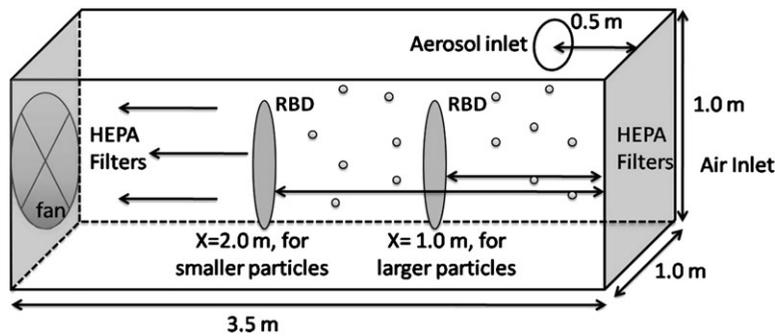


Fig. 2. Schematic of the wind tunnel showing aerosol inlet and location of the RBD for either larger (aerodynamic diameter $> 20 \mu\text{m}$) or smaller particle sizes.

ceiling, located 0.5 m downstream of the tunnel entrance (Fig. 2). The face of the RBD was positioned at two different locations relative to the aerosol injection point, as a function of particle size studied: 1.5 m downwind for particles $20 \mu\text{m}$ and smaller and 0.5 m downwind for larger particles, to accommodate gravitational settling of these particles in the slow-moving air.

RBD validation with isokinetic samplers

Validation of the RBD consisted of the following: (i) determining whether aerosol concentrations were spatially non-uniform within the wind tunnel test section and (ii) determining whether the RBD could account for such non-uniformity by rotating samplers in the wind tunnel cross section about an equal-area path during an experiment. Therefore, we placed isokinetic samplers both on and immediately surrounding the RBD to answer the aforementioned questions simultaneously. The isokinetic probes were made of stainless steel tubing (0.95 cm outer diameter, 0.67 cm inner diameter), each with a beveled edge leading into the flow. Probe inlets were then attached to 37-mm filter cassettes (Millipore Inc., Billerica, MA, USA) by drilling out the inlet cap and using epoxy to seal the inlet to the cap. The middle spacer piece of the 37-mm cassette was removed to minimize particle losses within the cassette. Flow through each isokinetic inlet was set at 0.87 l min^{-1} to match the probe sampling velocity with the wind tunnel free-stream velocity (0.4 m s^{-1}). Four isokinetic samplers were mounted on every other port on the RBD and four more were mounted at fixed locations around the RBD using ring stands. The fixed samplers were located as close to the edge of the RBD as possible without interfering with the rotation of the disc.

Monodisperse test aerosols of 10, 30, 50, and $100 \mu\text{m}$ aerodynamic diameter were generated using a Vibrating Orifice Aerosol Generator (model #3450,

TSI Inc., Shoreview, MN, USA) and an oleic acid solution tagged with ammonium fluorescein. Particle size was verified using a calibrated filar micrometer and bright field optical microscopy; measured particle diameters were monodisperse and generally within 15% of the expected physical diameter. At least three tests (four fixed and four rotating samplers per test) were completed at each particle size to compare the mean concentration and variance measured between the rotating and fixed isokinetic samplers. Although care was taken to replicate experimental duration and aerosol generation conditions among separate tests, the between-test aerosol concentrations were highly variable (up to 85% variation in daily mean concentration for $100 \mu\text{m}$ aerosol). However, despite the differences in mass concentrations, filter loadings never approached saturation and sampler flow remained constant from start to finish for a given test.

For measurements of 10, 30, 50, and $100 \mu\text{m}$ fluorescently tagged aerosols, collected particles were extracted and quantified using fluorescence detection. Filter substrates and isokinetic sampler inlets were placed in 15-ml centrifuge tubes and extracted with 4 ml of 3% ammonium hydroxide, enough to submerge the filters and inlets. The outside of the isokinetic sampler inlets was cleaned with an alcohol-wetted wipe to remove any aerosol that deposited on the outer surface of the inlet. Tubes were placed in a sonicator bath for 10 min to ensure efficient extraction. Three aliquots of $200 \mu\text{l}$ (i.e. triplicate samples) were pipetted into 96-well plates and analyzed in a fluorescence plate reader (FLX-800, BioTek Inc., Winooski, VT, USA). Results are reported in relative fluorescence units (RFU), which is a surrogate for mass, but of arbitrary magnitude. Calibration tests were run on the fluorometer to ensure linearity of the fluorescence signal over the range of concentrations sampled. The limit of

quantification for the fluorescence measurements was 10 RFU, corresponding to ~ 0.5 ng of fluorescein per sample; an experiment was only used if all measured values were above this limit.

Owing to both the large variability in aerosol concentration measured between tests (and the differences in analytical methods used for quantification, described below), results are presented in terms of relative concentration. Specifically, the concentration reported by each sampler from a given test was normalized by the mean concentration over all samplers from that test. Relative standard deviations, defined as the within-test standard deviation divided by the within-test mean times 100%, were also computed for each test. Student's *t*-tests were performed for each particle size to determine if average concentrations between rotating and fixed samplers were significantly different. Additionally, *F*-tests were performed to determine whether the relative standard deviations of measured concentrations were significantly reduced for samplers operating on the RBD as compared to the fixed case (one tail). Box-whisker plots were generated to allow visual comparison between test conditions.

RBD evaluation with open-faced 37-mm sampling cassettes

Following the isokinetic sampler tests, the performance of the RBD was evaluated using 37-mm polystyrene filter cassettes operated as open-faced samplers. The objective of these tests was to determine (i) whether the RBD rotation would reduce intra-sampler variation during wind tunnel testing of a common personal aerosol sampler and (ii) whether the orientation of the RBD relative to free-stream wind velocity affected its performance. Therefore, tests were conducted with the RBD operating under either rotating or non-rotating states and for the RBD oriented facing the wind (0° orientation) or away from the wind (180° orientation). At least three repetitions of a given aerosol type and RBD orientation (0° or 180°) were completed with the RBD rotating and non-rotating. In this case, all 37-mm cassettes were mounted on the RBD, so tests of non-rotating and rotating samplers were performed independently. Two types of test aerosols were generated to span the entire range of inhalable particle diameters. First, polydisperse calcium carbonate (CaCO_3) aerosol was generated using a Wright-type dust feeder, yielding an approximately lognormal particle distribution with a count median diameter of $1.74 \mu\text{m}$ and geometric SD of 2.12 (equivalent mass median diameter $9.5 \mu\text{m}$). The high deliquescence point and low hygroscopicity of CaCO_3 ensured that the particles did not

grow due to water adsorption in the wind tunnel. Second, monodisperse fluorescently tagged oleic acid aerosols of 20, 50, and $100 \mu\text{m}$ aerodynamic diameter were generated with the vibrating orifice aerosol generator. Again, care was taken to run samples for the same duration and generator operating conditions between tests, but the between-test aerosol concentrations were highly variable (up to 600% variation in daily mean concentration for $100 \mu\text{m}$ aerosol).

Aerosol concentration was determined by gravimetry for the CaCO_3 and $20 \mu\text{m}$ oleic acid aerosols. Samples were collected on Teflon-coated glass fiber filters (Pallflex Fiberfilm #T60A20). The filters were stored in a low relative humidity equilibration chamber for at least 12 h before obtaining pre- and post-sampling weights and were neutralized on a Polonium strip for at least 15 s prior to weighing. A Mettler-Toledo MX5 analytical microbalance (Columbus, OH, USA), accurate to $\pm 1 \mu\text{g}$, was used to obtain all weights. The mass of CaCO_3 collected on the filters was generally between 200 and $300 \mu\text{g}$, with a measured range from 110 to $550 \mu\text{g}$. The mass of oleic acid aerosol was much more variable, particularly when the RBD was fixed, but was generally between 100 and $400 \mu\text{g}$. All mass measurements exceeded our analytic limit of quantification for gravimetric analysis ($51 \mu\text{g}$), which is defined as five times the standard deviation of repeated blank weights.

For measurements of 20, 50, and $100 \mu\text{m}$ fluorescently tagged aerosols, collected particles were again extracted and quantified using fluorescence detection. As for the tests with isokinetic samplers, filter substrates were placed in 15 ml centrifuge tubes and extracted with 4 ml of 3% ammonium hydroxide. The spacer used to hold the filter in place for the open-faced 37-mm sampler tests was not extracted, only the filter. Filters were extracted and analyzed in the fluorescence plate reader as described in RBD validation with isokinetic samplers.

As for the tests with isokinetic samplers, results are presented in terms of relative concentration. Results were compiled into groups by particle size [1.74-count median diameter (CMD); 10, 20, 30, 50, and 100], RBD operation (non-rotating or rotating), and RBD orientation (facing the wind = 0° ; back to wind = 180°); box-whisker plots were generated to allow visual comparison between test conditions. In this case, *F*-tests alone were performed to determine if the standard deviations of relative concentration were reduced for the rotating tests as compared to the fixed case (one tail). Since the rotating and non-rotating tests of the 37-mm cassettes were performed independently, comparison of the mean concentrations is not appropriate.

Results: RBD validation with isokinetic samplers

We hypothesized that samplers operated on the RBD would measure similar mean concentrations, but with significantly reduced variability, as compared to fixed samplers. Results of the isokinetic sampler tests are presented in Table 1, including relative standard deviations within sampler groups (fixed or RBD-operated samplers), as well as *F*-values and *P*-values for the statistical tests between groups. Figure 3 is a box-whisker plot of relative concentrations collected during testing of the RBD with isokinetic samplers, as a function of particle diameter. The center line within the box indicates the median, the top and bottom of the box indicate the lower and upper quartile, and the whiskers extending above and below the box indicate the data range (excluding outliers). Outliers are defined as those data beyond 1.5 times the interquartile range and are denoted with a plus sign (+). Small boxes and whiskers indicate smaller variability than other boxes. The large reduction in variation between isokinetic samplers mounted on the RBD as compared to those in fixed locations is clear, indicating a high degree of spatial heterogeneity in aerosol concentrations across the 40 × 40 cm cross section of the wind tunnel where these samplers were positioned. As expected, these differences become more pronounced as particle size increased since larger particles (i.e. $d_p > 10 \mu\text{m}$) are more difficult to disperse about the wind tunnel cross section. For the fixed samplers, the relative standard deviation between samplers within an experiment was large, ranging from 5 to 53% for the 10 μm aerosol, 17 to 122% for 30 μm oleic acid aerosol, 53 to 245% for 50 μm aerosol, and 43 to 544% for 100 μm ammonium fluorescein tagged aerosol. The relative standard deviation between samplers operated on the RBD were smaller, ranging from 6 to 11% for the 10 μm aerosol, 5 to 27% for 30 μm oleic acid aerosol, 7 to 34% for 50 μm aerosol, and 5 to 130% for 100 μm . Results from the *F*-tests support these findings, indicating a significantly larger variance in concentrations measured

by the fixed samplers, for all sizes except 10 μm . Although large variances were observed both within and between tests, mean concentrations were not significantly different between the rotating and fixed sampler groups for any size (*P* values ranged from 0.13 to 0.52).

Analysis of variance was conducted to determine if the location of the sampler had an influence on the measured concentration. The concentration measured by the fixed sampler located above the RBD was significantly lower than the sampler located below the RBD for all sizes at the 95% confidence interval ($P < 0.04$), consistent with the expectations of gravitational settling of larger particles increasing the concentration near the wind tunnel floor in a low-velocity wind tunnel. The samplers mounted on the RBD were not significantly different from one another for any size at the 95% confidence interval.

Some within-test variation between samplers was anticipated due to minor variation in sampler flow rates, misalignment of the sampler in relation to the wind direction (<15%), blank contamination of fluorescent material, and/or contamination or loss of sample during filter processing and measurement. The flow rate through each sampler was set to within 2% of the nominal flow rate (0.87 l min⁻¹) prior to every test. Concentrations were calculated using the initial flow rate for each sampler during each test. The bias in sampled concentration due to sampler misalignment is very small for misalignment angles <15% and is expected to be negligible (Hinds, 1999). Finally, filter and sampler inlet blanks for the fluorescence were taken daily. Blanks were very low for all tests (0.5 ng), so the effect of mass gain or loss from filters and inlets is minimal.

Results: evaluation with 37-mm cassettes

Relative standard deviations for rotating and non-rotating 37-mm cassette samplers for each experimental condition are presented in Table 2. Figure 4 is a series of box-whisker plots of all relative concentrations collected during the RBD testing with

Table 1. Inter-comparison of variations in measured aerosol concentrations for isokinetic samplers operating under rotating and fixed conditions, as a function of particle size. The third column indicates the number of tests at that condition (eight samplers per test; four fixed and four mounted on the rotating RBD). The last columns present the *F*-value and *P*-value for each size; bold values indicate statistical significance at the 95% confidence interval

Orientation to wind	Aerosol type	Replicate tests	Relative SD (mean normalized)		<i>F</i> -value	<i>P</i> -value
			RBD	Fixed		
0°	Oleic acid (10 μm)	3	33	53	1.78	0.33
0°	Oleic acid (30 μm)	4	25	65	5.64	0.13
0°	Oleic acid (50 μm)	5	20	75	18.6	0.52
0°	Oleic acid (100 μm)	3	27	67	3.70	0.20

a 37-mm cassettes, as a function of RBD orientation and particle size.

Forward-facing tests (0° orientation). Within-test relative concentrations of all facing-the-wind tests (0° orientation) are shown in the left column of

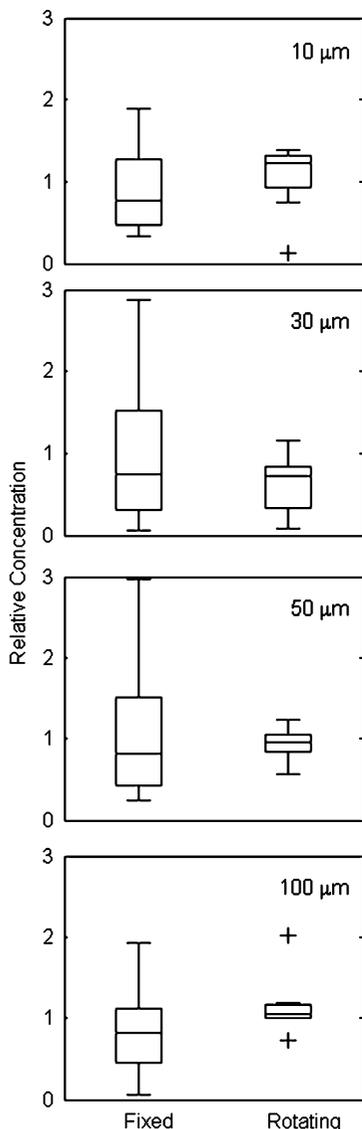


Fig. 3. Box-whisker plots of relative aerosol concentrations measured by isokinetic samplers mounted around the RBD (fixed) and on the RBD (rotating). Panels are separated by test aerosol diameter. The center of the box identifies the median, the limits of the box identify the lower and upper quartiles and the whiskers extend to 1.5 times the interquartile range from the ends of the box. Outliers are denoted with a plus sign. For aerosol $>30 \mu\text{m}$, rotating samplers mounted on the RBD have statistically reduced standard deviation of the concentration measurements compared to the fixed samplers ($F > 3.7$).

Fig. 4. The difference in measurement variation between non-rotating and rotating samplers is evident: When the RBD was not rotating, the relative standard deviation between open-faced 37-mm samplers within an experiment was substantial, ranging from 6 to 30% for CaCO_3 aerosol, 51 to 87% for $20 \mu\text{m}$ oleic acid aerosol, and 26 to 69% for 50 and $100 \mu\text{m}$ ammonium fluorescein-tagged aerosol. Although the variance was large, no clear bias was observed by location on the non-rotating disc for most sizes. Only for the $100 \mu\text{m}$ aerosol did analysis of variance indicate that concentrations toward the bottom of the disc were statistically higher than for samplers placed toward the top of the disk ($P < 0.001$). When the RBD was rotated, the relative standard deviation between samplers within an experiment was reduced to 5–15% for CaCO_3 aerosol, 10–19% for oleic acid aerosol, and 7–41% for 50 and $100 \mu\text{m}$ ammonium fluorescein aerosol. The impact of RBD rotation was somewhat reduced for the smaller particle sizes, which is not surprising, since smaller particles are more easily dispersed throughout the tunnel. The F -tests showed that, for all forward-facing experiments, the standard deviation of the experiments when the RBD was spinning was significantly lower than for the experiments when the RBD was not spinning, at the 95% confidence level, even for the polydisperse CaCO_3 , for which the CMD was $<2 \mu\text{m}$ ($F = 3.2$).

As with the isokinetic sampler tests, some within-test variation between 37-mm samplers was anticipated due to flow deviations, sampler alignment, and blank variation. The flow rate through each sampler was set to within 5% of the nominal flow rate (2 l min^{-1}) prior to every test. Concentrations were calculated using the initial flow rate for each sampler during each test. Measured flow rates at the end of a test generally varied from the initial flow rate by $<0.03 \text{ l min}^{-1}$. Daily filter blanks were very low for all tests ($10 \mu\text{g}$ for gravimetric measurements and 0.5 ng for fluorescence measurements), so the effect of mass gain or loss from filters was minimal.

Rear-facing tests (180° orientation). Within-test relative concentrations of all back-to-the-wind tests (180° orientation) are shown in the right column of Fig. 4, as a function of particle size. Here, the differences in measurement variation between rotating and non-rotating samplers are less pronounced, as opposed to the forward-facing tests. When the RBD faced backward to the wind and was non-rotating, the relative standard deviation between samplers within an experiment ranged from 5 to 11% for CaCO_3 aerosol, 8 to 14% for $20 \mu\text{m}$ ammonium fluorescein tagged oleic acid aerosol, and 11 to 33% for

Table 2. Inter-comparison of variations in measured aerosol concentrations for open-faced 37-mm cassette samplers, by particle size, RBD rotation mode (rotating, non-rotating), and RBD orientations relative to the air velocity in the wind tunnel [facing the wind (0°) and rear to the wind (180°)]. The third column indicates the number of tests at that condition (eight samplers per test). The last column presents the F -value for each case, bold values indicate statistical significance at the 95% confidence interval

Orientation to wind	Aerosol type	Replicate tests	Relative SD (mean normalized)		F -value
			Rotating	Non-rotating	
0°	CaCO ₃ CMD = 1.74 μm , $\sigma = 2.12$	3	8	14	3.19
180°	CaCO ₃ CMD = 1.74 μm , $\sigma = 2.12$	5	7	8	1.14
0°	Oleic acid (20 μm)	3	15	64	18.11
180°	Oleic acid (20 μm)	3	7	9	1.54
0°	Oleic acid (50 μm)	5	20	38	3.51
180°	Oleic acid (50 μm)	3	23	20	1.42
0°	Oleic acid (100 μm)	5	22	85	14.5
180°	Oleic acid (100 μm)	3	37	17	0.22

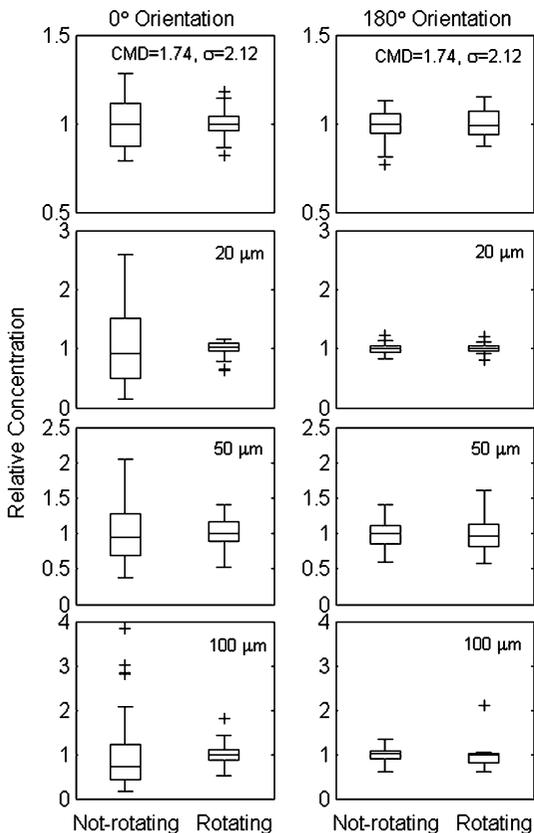


Fig. 4. Box-whisker plots of relative aerosol concentrations measured by open-faced 37-mm cassette samplers mounted on the RBD and operated in either rotating or non-rotating condition. The left column presents data for experiments with 0° orientation (facing-the-wind) and the right column for 180° orientation. Panels are separated by test aerosol diameter. The center of the box identifies the median, the limits of the box are the lower and upper quartile, and the whiskers extending to 1.5 times the interquartile range from the ends of the box. Outliers are denoted with a plus sign.

50 and 100 μm ammonium fluorescein aerosol. When the RBD was rotated, the relative standard deviation between samplers within an experiment was comparable: 7–9% for CaCO₃ aerosol, 3–12% for oleic acid aerosol, and 3–68% for 50 and 100 μm ammonium fluorescein aerosol. Further, the F -tests showed that the standard deviation was not significantly reduced when the RBD was rotating compared to the non-rotating condition for all sizes. The lack of effect from RBD rotation for the 180° orientation is likely due to the turbulence created in the flow by the RBD (flow Reynolds number $> 10\,000$ for a 40-cm disc at 0.4 m s^{-1}). Thus, the aerosol was better mixed downstream of the RBD, which diminished the effect of rotation.

APPLICATION OF THE RBD

Aspiration efficiency of Institute of Occupational Medicine samplers

Having validated the RBD performance, we sought to apply this device for aspiration efficiency tests of a common personal aerosol sampler, the Institute of Occupational Medicine (IOM) personal sampler (SKC Inc., Eighty Four, PA, USA). The IOM personal sampler is commonly used to estimate workers' exposure to 'inhalable' particles in the workplace. Two isokinetic probes identical to those used in the RBD validation were mounted on the RBD as well as two IOM samplers. Again, separate experiments were performed with the RBD both rotating and non-rotating; for this work, only the forward-facing orientation was explored. Tests were conducted with 10, 30, 50, and 100 μm aerodynamic diameter particles of fluorescently tagged oleic acid and generated using the vibrating orifice aerosol generator. The filter and the

inlet of the IOM sampler were extracted separately for analysis. Isokinetic and IOM sampler blanks were taken daily. The wind tunnel air velocity was maintained at 0.4 m s^{-1} , so the operating flow rate of the IOM (2 l min^{-1} ; 0.19 m s^{-1} face velocity) was not isokinetic with the air velocity, instead being subisokinetic. As a result, the IOM was likely to modestly overestimate the aerosol concentration in our tests. For these tests, aspiration efficiency of the IOM is defined as the measured IOM fluorescence concentration divided by the mean concentration reported by the two isokinetic samplers for each test. The variance was calculated using a propagation of errors accounting for the variance in both the IOM measured concentration and the isokinetic sampler measured concentration.

Results and discussion

Measured aspiration efficiencies of the IOM sampler were similar in magnitude ($P > 0.25$ for all sizes) for the rotating and non-rotating cases, as shown in Fig. 5. However, measurement variance for the rotating case was significantly reduced for all sizes except the $30 \mu\text{m}$ aerosol, which was reduced, but not significantly at the 95% confidence interval ($F = 1.79$). A comparison between IOM aspiration efficiency measured here (facing-the-wind tests) and the orientation-averaged inhalability curve would be inappropriate. Instead, the aspiration efficiency of the IOM was compared to human inhal-

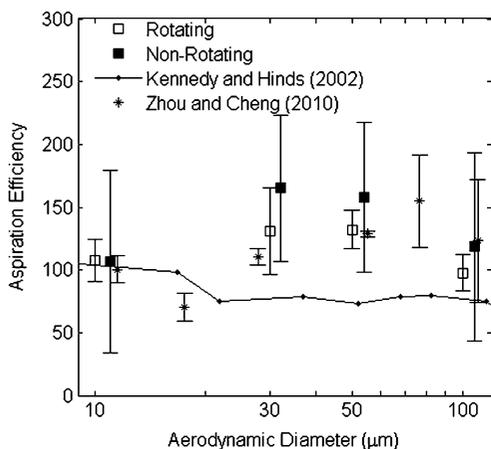


Fig. 5. Forward-facing aspiration efficiency of IOM samplers operating on the RBD in either rotating or non-rotating modes. Points for the non-rotating modes are offset from the selected size for clarity only. Inhalability data for facing-the-wind, mouth-breathing from Kennedy and Hinds (2002), and estimated facing-the-wind aspiration efficiency of the IOM from Zhou and Cheng (2010) are shown for comparison. Error bars represent one standard deviation.

ability in Fig. 5 for facing-the-wind mouth breathing as reported by Kennedy and Hinds (2002). The IOM overestimated the facing-the-wind inhalability for all particle sizes $>10 \mu\text{m}$. The overestimation due to the anisokinetic flow is expected to range from 2 to 75% for the range of particle sizes tested (Hinds, 1999), which is in agreement with the data presented in Fig. 5. The mass collected on the IOM inlet as a percentage of the total mass collected increased from 16% for the $10 \mu\text{m}$ particles to as high as 60% for the larger particles. It is possible that, particularly for the large aerosol, the large aspiration efficiency is due, in part, to aerosol impacting on the outer portion of the IOM inlet. Solid particles might bounce off the inlet, whereas all liquid aerosol will deposit. This is an important consideration when using an IOM in an environment where liquid aerosol may be present.

Orientation-averaged aspiration efficiencies for personal samplers are often reported in the literature (e.g. Kenny *et al.*, 1997; Paik and Vincent, 2004), but such measurements should not be compared to facing-the-wind aspiration efficiencies. Instead, we compare our results to other studies that tested IOM aspiration efficiency under a non-rotating orientation. Zhou and Cheng (2010) performed aspiration efficiency tests of the IOM in a wind tunnel operating at 0.56 m s^{-1} and with fluorescently tagged, monodisperse oleic acid aerosols. IOM samplers were mounted on the front, side, and back of a manikin, with results given separately. Two isokinetic samplers were located to either side of the manikin in their study, yet there is no mention of variability observed between the isokinetic samplers. We have included the Zhou and Cheng (2010) facing-the-wind estimated aspiration efficiencies of the IOM on Fig. 5 for comparison. Zhou and Cheng reported forward-facing aspiration efficiencies between 80 and 150%, with the largest values for particles near $100 \mu\text{m}$. However, they observed a minimum in aspiration efficiency $\sim 30 \mu\text{m}$, whereas we observed a maximum in aspiration efficiency at this size.

Other studies using solid aerosol have found somewhat smaller aspiration efficiencies. Kenny *et al.* (1997) reported aspiration efficiencies $<100\%$ for particle diameters up to $100 \mu\text{m}$ using Aloxit powder aerosol. Kennedy *et al.* (2001) reported an aspiration efficiency of $\sim 150\%$ for the IOM sampling $120 \mu\text{m}$ alumina oxide powder but aspiration efficiencies $<100\%$ for smaller diameters. However, Li *et al.* (2000) reported measured aspiration efficiency of the IOM for 0° , 90° , and 180° orientations for free-standing samplers (i.e. not mounted on a manikin or bluff body). Solid ammonium fluorescein aerosol

with diameters between 5 and 68 μm were used in a wind tunnel at a wind velocity of 0.55 m s^{-1} . The IOM aspiration efficiency was $\sim 100\%$ for the 5 μm aerosol and increased to $\sim 200\%$ for 68 μm aerosol. The somewhat larger aspiration efficiencies we observed and those observed by Zhou and Cheng (2010) may be partially attributed to the liquid phase of the aerosol since droplets will not bounce off the forward-facing edge of the IOM cassette. The use of the manikin may also explain some of the differences between that study and the results presented here, although all the aforementioned studies observed higher facing-the-wind aspiration efficiency for the IOM than is predicted for human mouth breathing (Kennedy and Hinds, 2002).

We note that for all the tests reported here, the RBD accounted for $\sim 12.5\%$ of the cross-sectional area of the wind tunnel, which may have affected air velocity profiles in the test section. Often a blockage ratio $< 10\%$ is recommended for wind tunnel studies (Vincent, 1989). However, detailed model simulations suggest that blockage ratios up to 15% have limited impact on the wake properties in the wind tunnel (Anagnostopoulos *et al.*, 1996). Therefore, we recommend that the RBD be used in tunnels for which the disc blocks $< 15\%$ of the cross-sectional area of the tunnel.

CONCLUSIONS

An RBD was found to improve agreement between personal aerosol samplers operating in a wind tunnel. The RBD allowed comparison of up to eight personal samplers that rotated through identical paths to minimize the variability (and potential bias) associated with non-uniform aerosol concentrations typical of low-velocity wind tunnels. This design represents an advance in representative sampling with multiple personal samplers and sampler types. The RBD was able to constrain the uncertainty in determining facing-the-wind aspiration efficiency of a commonly used personal aerosol sampler, the IOM. One limitation, however, is that the RBD, in its current form, has limited use in orientation-averaged testing. The RBD would have to be manually turned in the tunnel and separate tests at different orientations would need to be conducted, as was done here for 0° and 180° orientations, with fixed isokinetic probes located in the tunnel. However, a more sophisticated compact RBD could be built with two axes of rotation allowing isokinetic samplers to always face the wind, while the disc on which the personal samplers were mounted could operate on a turntable. However, the influence on aspiration efficiency due

to the turbulence generated downwind of such a design may vary from that generated by a human. Future research may address this modification. This study also did not examine the effect of RBD rotation rate on measured concentration, although we expect that effect to be minimal, when the periodicity of rotation greatly exceeds the test duration.

The RBD provides a method to reduce spatial variability for personal sampler evaluation when a uniform aerosol concentration in a wind tunnel cross section is unachievable. Reduced variability of the aerosol concentration will improve statistical power, which is critical to reduce the number of wind tunnel tests needed. Since wind tunnel testing is time and resource intensive, the RBD can be used to test multiple samplers and also multiple sampler types reliably and simultaneously, reducing the cost of sampler evaluations. The RBD can be scaled for use in any wind tunnel, where its size should be determined from the needed area over which spatial variability is critical; however, recommendations are given to minimize the blockage ratio of the RBD to the wind tunnel cross-sectional area to $< 15\%$. The RBD may also be used for aerosol sampler comparisons in the field, when operated as an area monitor, for locations with high spatiotemporal variability in aerosol concentration.

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