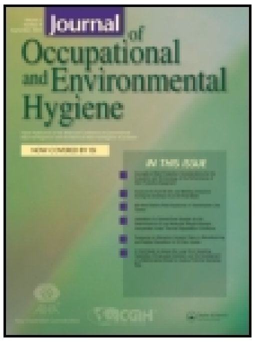

Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: http://www.tandfonline.com/loi/uoeh20

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To cite this article: Patrick T. O'Shaughnessy , Julie Lo , Vijay Golla , Jason Nakatsu , Marvin I. Tillery & Stephen Reynolds (2007) Correction of Sampler-to-Sampler Comparisons Based on Aerosol Size Distribution, Journal of Occupational and Environmental Hygiene, 4:4, 237-245, DOI: 10.1080/15459620701193533

To link to this article: http://dx.doi.org/10.1080/15459620701193533

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Journal of Occupational and Environmental Hygiene, 4: 237–245
ISSN: 1545-9624 print / 1545-9632 online
DOI: 10.1080/15459620701193533

Correction of Sampler-to-Sampler Comparisons Based on Aerosol Size Distribution

Patrick T. O'Shaughnessy,[1] Julie Lo,[2] Vijay Golla,[1] Jason Nakatsu,[3] Marvin I. Tillery,[3] Stephen Reynolds[3]

[1]The University of Iowa—Occupational and Environmental Health, Iowa City, Iowa
[2]Carolina Environmental Inc., Cary, North Carolina
[3]Colorado State University—Department of Environmental and Radiological Health Services, Fort Collins, Colorado

This article explains a simple method for correcting a sampler-to-sampler ratio for changes in size distribution by computing a bias factor that relates the measured ratio with a ratio determined from equations that describe the collection efficiency curves of the samplers while taking size distribution into account. Laboratory trials were conducted to determine whether the resulting bias factor is independent of aerosol size distribution. During these studies, a 3-piece cassette and respirable cyclone were compared with an inhalable sampler in both a still-air chamber and a moving-air chamber operated at 0.2 m/sec and 1.0 m/sec. An ISO test dust of various size fractions was generated to produce an aerosol with mass median aerodynamic diameter ranging from 1.4 μm to 10.1 μm. An organic dust consisting of ground grain material was also applied to the still-air chamber to demonstrate differences between dust types. Results showed that the bias value was significantly different between dust types for both the cyclone/inhalable ($p = 0.001$) and cassette/inhalable ($p = 0.033$) comparisons but was not different between wind conditions for either comparison. All but one comparison had insignificant slopes when comparing the bias value with median diameter, indicating that the bias value could be used to correct for size distributions in most conditions. However, bias values determined when comparing the cyclone with the inhalable sampler in the still-air condition produced a positive slope for median diameters less than 4 μm ($p = 0.008$). Further research is needed to determine why the actual cyclone/inhalable ratio decreases relative to the expected ratio as the proportion of respirable particles increases. These results suggest that, for most conditions, the size-distribution compensation can be applied to sampler-to-sampler correlations provided that the original comparison was performed with the same dust type.

Keywords aerosol samplers, correlation analysis, normalization technique

Address correspondence to: Patrick O'Shaughnessy, The University of Iowa, Occupational and Environmental Health, 100 Oakdale Campus, 137 IREH, Iowa City, IA 52242; e-mail: patrick-oshaughnessy@uiowa.edu.

INTRODUCTION

Given the long history of sampling for airborne dust levels in occupational settings, a variety of aerosol sampling devices have been developed. Reference methods were developed to determine "total dust" concentrations with the use of a filter housed in a 3-piece plastic cassette[(1)] and "respirable dust" concentrations using a plastic cassette to house the filter and a small cyclone to eliminate the large particles.[(2)] With the acceptance of collection efficiency curves developed to define an inhalable, thoracic, and respirable fraction of the total dust,[(3)] personal size-selective samplers have been purposely designed to achieve aerosol collection efficiencies relative to particle size that closely follow the definitions. Therefore, an important aspect of recent research on aerosol samplers has been related to characterizing their collection properties.

Sampler characterization studies have been conducted under two basic premises: (1) to determine the collection efficiency curve of the device over a range of particle diameters, or (2) to compare different samplers by correlation of side-by-side measurements. The typical procedure for determining sampler collection efficiency is to attach the samplers to a rotating mannequin in a wind tunnel, produce a monodisperse aerosol of various sizes, and determine the concentration measured by the sampler relative to that of an isokinetic probe.[(4–8)] Other sampler efficiency studies involved the use of a particle counter to determine the difference in counts obtained with the sampler attached to the counter relative to when it was detached from the counter.[(9–13)] There has also been recent interest in characterizing samplers in controlled calm-air conditions under the premise that many occupational settings, such as those occurring in large manufacturing facilities, contain work areas with a low air exchange rate.[(14–16)]

Sampler correlation studies are typically performed in the field with multiple samplers worn on subjects,[(17–19)] arranged as area samplers,[20–22] or attached to a mannequin[23,24] while sampling the dust generated in an occupational setting. A primary aim of these studies has been to determine a proportional relationship between two different samplers. A motivation for this aim is the comparison of measurements made in the past with one sampler type relative to current measurements made with a different sampler. Such a relationship would be important when conducting a retrospective epidemiologic study of worker exposures in an industry that has been evaluated with different samplers to accurately compare present exposure levels with past levels. For example, many studies in the past involved the use of a closed-face 37-mm cassette as per NIOSH method 0500,[1] whereas present studies often involve the use of a sampler with a size-selective inlet to collect the inhalable fraction of dust. A proportional relationship between two samplers with different collection characteristics may also be useful for predicting the respirable fraction of dust in a workplace with measurements made with an inhalable sampler, for example.

Typically, a "slope factor" is reported in sampler correlation studies that directly relates the concentrations measured by two different samplers.[17–20,22,23] This value is obtained from a linear regression of the concentrations measured by the paired samplers while forcing the intercept to zero. Some studies of this type have also reported the ratio of all measurements taken with one sampler relative to those taken by the paired sampler.[17,20–24] Regardless of the value reported, the result will be dependent on the size distribution of the aerosol measured, which implies that the reported result will not be valid if the size distribution differs in some other setting. The following section describes a method that can be used to compensate for changes in aerosol size distribution when attempting to predict measurements made with one sampler type based on actual measurements made with a different sampler. Subsequent sections describe results from a study conducted to validate this approach.

Size Distribution Correction

The ratio of the concentration measurements made with one sampler relative to a different sampler will not be unity if the samplers' collection efficiency curves differ. For example, the closed-face cassette collects larger particles with less efficiency than the Institute of Medicine (IOM) sampler, which was designed to measure the inhalable dust fraction, and is therefore expected to provide a lower concentration measurement for the same environment.[5] The same is obviously true when comparing measurements taken with a respirable cyclone relative to the IOM. Using a respirable cyclone and inhalable sampler as examples, the ratio of their measurements can be predicted for any aerosol size distribution if (*a*) the samplers collect with exactly the same efficiency as that described by the equations that define the respirable and inhalable curves, and (*b*) the aerosol size distribution is perfectly lognormal. In this case, a cascade impactor could be used to determine the mass median aerodynamic diameter, d_g, and geometric standard deviation, σ_g, needed to characterize the aerosol size distribution. With those distribution parameters, the mass probability density function (PDF) of the total size distribution, f_t, can be computed over a range of aerodynamic diameters, d_{ae}, using the equation for the PDF of a lognormally distributed variable.[25] Likewise, the size distribution, f_R, that defines the fraction of the aerosol collected by a cyclone that collects in accordance with the respirable definition can be determined as given in Eq. 1:

$$f_R = \eta_R(d_{ae}) f_t(d_{ae}, d_g, \sigma_g) \tag{1}$$

where $\eta_R(d_{ae})$ defines the respirable efficiency curve. The same process can be applied to determine the size distribution, f_I, that defines the fraction of the aerosol collected by a sampler that collects in accordance with the inhalable definition. Under the assumption that both samplers collect with the same flow rate, the expected ratio of mass collected by the cyclone to the mass collected by an inhalable sampler, $E_{R/I}$, is then the ratio of the cumulative distributions of the two PDFs:

$$E_{R/I} = \frac{\int f_R dd_{ae}}{\int f_I dd_{ae}} \tag{2}$$

An example of this method applied to two different size distributions is given in Figure 1. Values for $E_{R/I}$ over a range of d_g and σ_g values typical of those found in occupational settings is given in Figure 2.

There would be no reason to take side-by-side samples in workplaces to determine a ratio empirically if the two assumptions mentioned above held true in all cases. However, several factors can cause a difference, or bias, between the expected ratio and one determined empirically. These factors include sampler orientation relative to a moving air source and air velocity as well as physical and environmental factors such as particle shape and electrostatic effects. The result is a collection efficiency curve that varies in some manner from the ideal curve. For some cyclones, such as the SKC aluminum cyclone, an inherent difference also exists between the shape of its collection efficiency curve and the respirable definition that will cause a bias dependent on aerosol size distribution.[26] An early discussion of bias error associated with the nature of the sampler efficiency curve relative to a size convention is given by Bartley and Doemany.[27]

Given the biases inherent to sampling devices, the actual concentration ratio between any two samplers can be expressed as:

$$\frac{C_1}{C_2} = E_{1/2} \times \frac{Bias_1}{Bias_2} \tag{3}$$

In practice, the bias associated with an individual sampler cannot be determined because the many factors that contribute to the bias are not directly measurable. However, the bias ratio can be calculated simply by inverting Eq. 3:

$$\text{Bias Ratio} = \frac{C_1/C_2}{E_{1/2}} \tag{4}$$

If the bias ratio is determined during a study of a particular occupational setting, this value, together with knowledge of the aerosol size distribution of any similar setting, can then

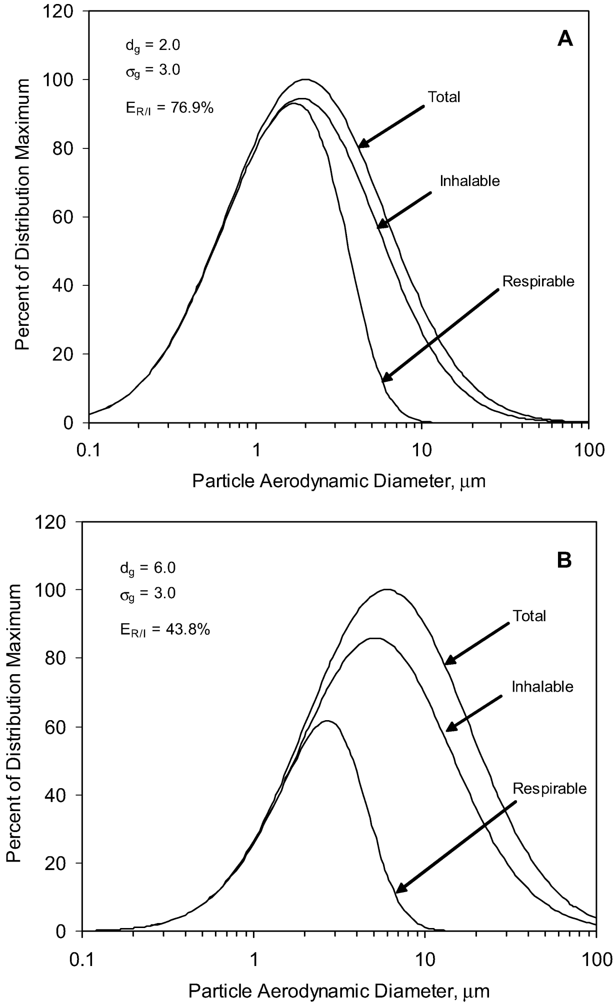

FIGURE 1. Theoretical size distributions associated with the respirable and inhalable sampling efficiency curves for an aerosol with a lognormal size distribution and mass median aerodynamic diameter, d_g, of (A) 2.00 μm and (B) 6.00 μm

be applied for other settings to determine the actual ratio by solving Eq. 4 for C_1/C_2. Reporting the bias ratio therefore allows subsequent researchers to compensate the actual ratio for changes in aerosol size distribution

The compensation method described above operates under the assumption that, for a particular occupational setting, all other factors that contribute to the value of the bias ratio other than a change in size distribution remain constant. This assumption was tested through a series of laboratory-based experiments involving different environmental conditions (changes in wind velocity) for one dust type with a varying size distribution and between dust types with an equivalent size distribution.

METHODS

Three commonly used aerosol samplers were evaluated: the 37-mm closed-face cassette (CFC), the IOM inhalable sampler, and the SKC aluminum respirable cyclone (all available from SKC Inc., Eighty Four, Pa.). Flow rates for each sampler were adjusted with a needle valve and calibrated to within 5% of the suggested flow rate before each trial with an electronic soap bubble flow meter (Gilibrator, Sensidyne, Clearwater, Fla.). Flow rates of 2.0 L/min and 2.5 L/min were set according to manufacturers' instructions for the IOM and cyclone, respectively. A flow rate of 2.0 L/min for the CFC was chosen from the suggested range of 1–2 L/min.[1] Filters (5 μm polyvinyl chloride) were weighed with the use of a 6-place balance (Model MT5, Mettler-Toledo Inc., Columbus, Ohio). The samplers were applied to two different chambers, one to mimic "still air" conditions and one in which flowing air was applied.

Still-Air Chamber Trials

The samplers were attached to a stationary mannequin (torso and head) in a 1-m^3 Rochester-style chamber[28] operated with a total flow rate (chamber flow and generator flow) of 42 L/min (Figure 3). Given a cross-sectional area of 1 m^2, this flow rate resulted in a downward velocity of air of only 0.07 cm/sec, equivalent to the settling velocity of a 5 μm particle and much less than a criteria of $<$0.1 m/sec used by others for very slow moving air.[16] Two aerosols were produced: ISO test dust (Powder Technologies, Burnsville, Minn.) with a density of 2.7 g/cc, and an organic dust collected at a grain elevator and ground with a ball mill (Glen Mills Inc., Clifton, N.J.) with a much lower density of 1.56 g/cc. Three different forms of the ISO dust were purchased (fine, medium, and coarse) to expand the range of median diameters produced. The grain dust has been used in a previous study to represent a relatively homogenous dust of organic origin and with a size distribution similar to the inorganic ISO dust.[29] The aerosols were generated by a Wright dust feed (BGI Inc., Waltham, Mass.) and passed through a radioactive deionizer (^{63}Ni) before entering the main volume of the chamber. This aerosol-generating device was designed for inhalation studies to produce a consistent amount of micrometer-sized particles.[30] The deionizer was applied to minimize any collection effects that may be attributable to electrostatic effects.

An 8-stage cascade impactor (Marple 290, Thermo-Electron Corp., Waltham, Mass.) was used to determine the size distribution of the aerosol during each trial. This impactor has cut diameters ranging between 0.52 μm and 21.30 μm. The d_g and σ_g values were determined by first applying correction factors to account for stage losses[31] and then plotting the cumulative frequency of mass on each stage versus stage cut diameter on log-probability paper.[25]

A pair of each sampler type was applied to the mannequin during each trial. One of each of the three samplers was randomly located across the front of the mannequin, and the corresponding sampler was placed on the other side of the mannequin and directly opposite to its pair. An initial analysis was conducted to determine the spatial uniformity of dust concentrations inside the chamber. Four trials were performed during which six CFC samplers were attached to

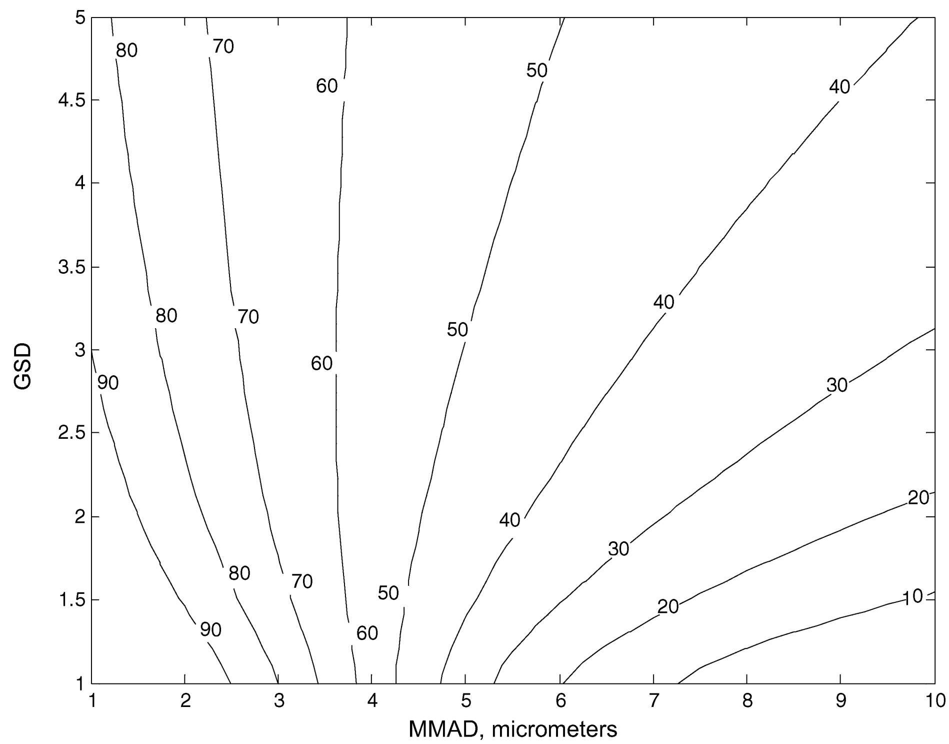

FIGURE 2. Contour map of the ratio (%) of respirable particles to inhalable particles over a range of mass median aerodynamic diameters (MMADs) and geometric standard deviations (GSD) that define the lognormal distribution of the aerosol

the mannequin, three front and three back. An analysis-of-variance of the four trials showed no significant difference between locations ($p = 0.187$), and an overall coefficient of variation (CV) was 8.0%.

Wind Tunnel Trials

A wind tunnel with a 1-m^2 cross-sectional area[32] was also used as part of this research to determine sampler performance under horizontal wind velocities of 0.2 m/sec and 1.0 m/sec (Figure 3). Samplers were placed on a revolving mannequin (torso and head) in the wind tunnel. During these trials only the ISO test dust was produced with the use of an NBS dust feeder (not currently manufactured).[30] Eight trials of 180-min duration were performed for each flow rate. Sampler flow rates were identical to those described above. An 8-stage, nonviable cascade impactor (Series 20-800 Mark II, Thermo-Electron Corp.) was used during wind tunnel experiments to determine the aerosol size distribution. This impactor has cut diameters ranging between 0.50 μm and 14.20 μm. Although unsubstantiated in the literature, this impactor was used in the wind tunnel instead of the Marple personal impactor because it is commonly used as an area sampler that may be less influenced by wind direction and speed.

Sampler Comparisons

An average for each pair of the same sampler used in each trial was computed. Sampler comparisons were then made by determining the ratio of the pair average of one sampler versus that of another sampler. This measured ratio was then compared with a ratio developed under the assumption that the samplers collected according to a defined collection efficiency curve. For this analysis, the IOM and cyclone were assumed to have a collection efficiency curve equivalent to the equation describing the American Conference of Governmental Industrial Hygienists (ACGIH®) inhalable and respirable fraction, respectively.[3] A collection curve for the CFC was determined from data given by Mark et al.[5] that was based on the general form of the equation used to define the inhalable curve (Eq. 5). This equation produced an asymptotically decreasing curve forced through a fractional efficiency, $\eta = 1$, when the diameter is 0 and an asymptote, c, greater than an efficiency of $\eta = 0$.

$$\eta = (1 - c)\, e^{-kd} + c \quad \textbf{(5)}$$

Values of $c = 0.140$ and $k = 0.045$ produced a curve with an r^2 value of 0.89 relative to the nine data points given by Mark et al.[5] (Figure 4). By comparison, $c = 0.50$ and $k = 0.06$ for the inhalable definition.

In practice, dusts sampled from occupational settings are often not perfectly lognormal. However, the calculation of the expected ratio, E, by application of Eq. 2 relies on the use of the equation for the PDF of a lognormally distributed variable. Therefore, this equation is computed under the presumption that the distribution is perfectly lognormal and that the two parameters, d_g and σ_g, accurately describe the size distribution

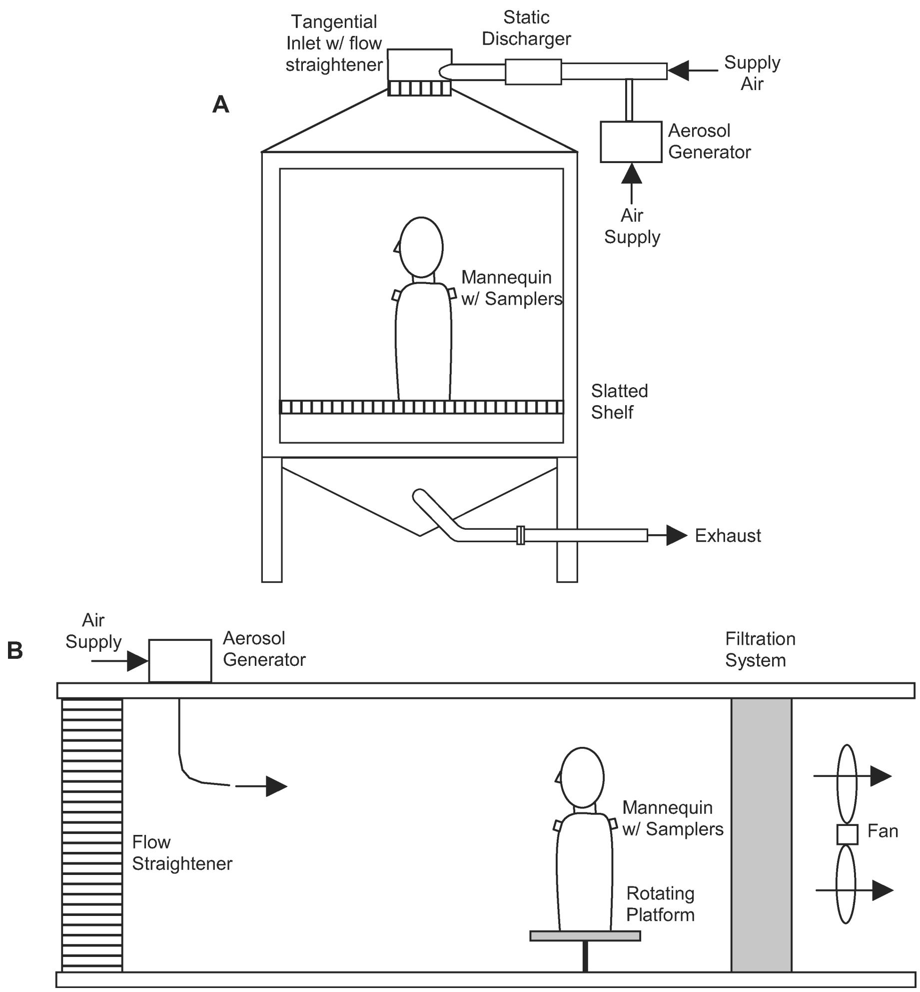

FIGURE 3. Schematic diagram of still-air (A) and wind-tunnel (B) test chambers

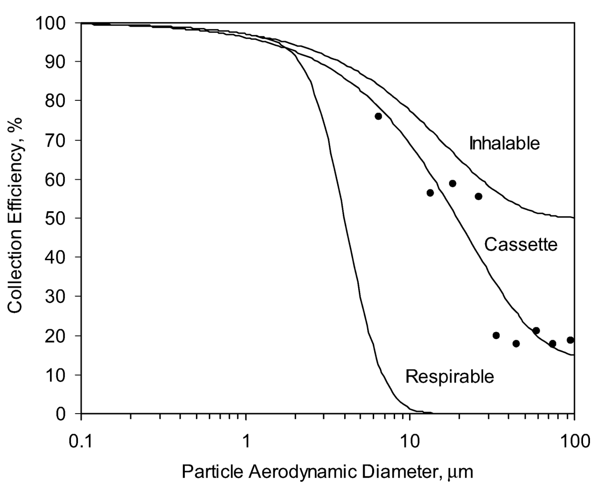

FIGURE 4. Collection efficiency curve of the closed-face cassette relative to the collection efficiency values measured by Mark et al.[5] and the ACGIH respirable and inhalable curves[3]

when applied to the equation. To compensate for deviations from a perfectly lognormal distribution, the equations for the three collection efficiency curves shown in Figure 4 were used to determine the average collection efficiency for all particles with diameters ranging between the cut-off diameters of the eight impactor stages of the cascade impactors used in this study (Table I). These efficiency values were then applied to the mass collected on each stage to determine the expected mass percentage of respirable, inhalable, and CFC dust produced during a trial. This method, therefore, can be used to accurately determine the expected ratio regardless of the aerosol's size distribution.

RESULTS

Bias ratio values for the dust types and conditions associated with this study are given in Figure 5. A t-test demonstrated that for all cases combined, the cyclone/IOM bias ratio was significantly lower than the cassette/IOM bias

TABLE I. Sampler Collection Efficiencies Corresponding to Each Impactor Stage

Stage[A]	Cut Diameter (μm)	Respirable Collection Efficiency (%)	Inhalable Collection Efficiency (%)	CFC Collection Efficiency (%)
1	21.3	0.000	54.838	27.686
2	14.8	0.027	67.583	53.254
3	9.8	0.622	74.621	64.546
4	6.0	8.199	81.906	75.399
5	3.5	40.254	88.144	84.207
6	1.6	84.296	93.409	91.351
7	0.9	96.409	96.554	95.520
8	0.5	97.975	97.976	97.379

[A]Thermo-Electron (formerly Anderson) Series 290 personal 8-stage impactor.

ratio ($p < 0.001$). Although the average bias ratio level for each condition analyzed was less than 1, the average cassette/IOM bias ratio was not significantly different than 1 for trials involving the ISO dust at 0.2 ($p = 0.086$) and 1.0 m/sec ($p = 0.286$). Furthermore, the relatively close approximation of the cassette/IOM bias ratio to 1 for all conditions analyzed suggests that the collection efficiency defined by Eq. 5 is an acceptable model for describing the collection efficiency curve of the 3-piece cassette.

As shown in Figure 5, the overall average of bias ratio values for the different wind conditions applied to the ISO dust trials varied but were not significantly different for either the cyclone/IOM bias ratio ($p = 0.114$) or the cassette/IOM bias ratio ($p = 0.127$) as indicated by a one-way analysis of variance. However, the bias ratio values obtained for the grain dust were significantly lower than the ISO bias ratio values produced in the still-air chamber for both the cyclone/IOM bias ratio ($p = 0.001$) and the cassette/IOM bias ratio ($p = 0.033$). This analysis was performed with a t-test comparing seven ISO trials relative to nine grain-dust trials, which produced nearly equivalent average median diameters (5.04 μm and 5.12 μm, respectively) to negate any possible influence on the bias ratio values from differences in size distribution.

To effectively use a bias ratio value as given in Eq. 4 to correct a sampler ratio for changes in size distribution, the bias ratio value must be independent of changes in the aerosol size distribution. To test this assumption, a linear regression of bias ratio relative to d_g was performed and the resulting slope was tested to determine whether it was significantly different from zero. Although the bias ratio value is also affected by the geometric standard deviation of the size distribution, this analysis allowed for a reasonable approximation of whether particle size affects the bias ratio value. Furthermore, a multiple linear regression involving both d_g and ${}_g$ values as independent variables relative to the cyclone/IOM bias ratio as the dependent variable revealed that the coefficient associated with σ_g values was not significant ($p = 0.691$). Results for all trial conditions are given in Table II where it can be seen that all slopes were insignificant except that associated with the cyclone/IOM bias ratio ($p = 0.001$) when sampling the ISO dust in the still-air chamber. Further analysis of this bias ratio demonstrated that the slope of the points with d_g less than 4 μm was significant ($p = 0.008$) whereas the slope for points with d_g greater than 4 μm was insignificant ($p = 0.728$) (Figure 6). Furthermore, the average of these bias ratio values greater than 4 μm was 1.01 and not significantly different from 1 ($p = 0.921$).

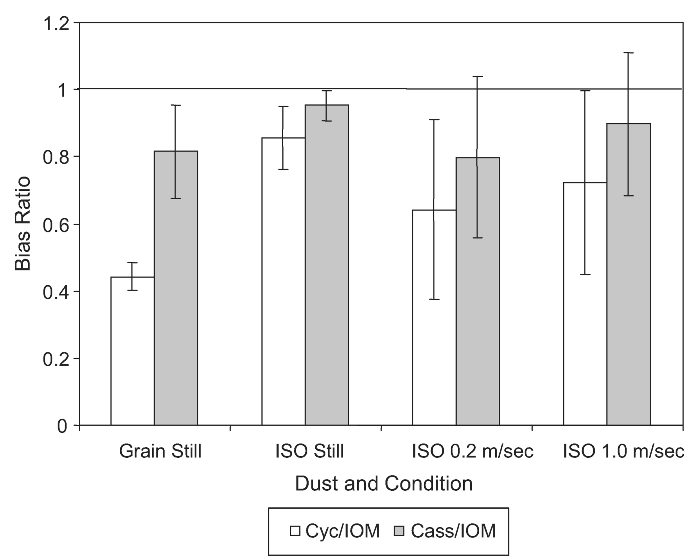

FIGURE 5. Average bias ratio values (with 95% confidence bars) for two dust types and three wind conditions

TABLE II. Slope and Related p-Value of Linear Regression Associating Bias Ratio Values with Mass Median Aerodynamic Diameters (d_g) and Geometric Standard Deviation (σ_g) for Each Trial Condition

Dust and Trial Condition	n	d_g Range	σ_g Range	Cyclone/IOM Slope (p-value)	Cassette/IOM Slope (p-value)
Grain—still air	9	2.05–7.46	2.68–5.78	0.022 (0.111)	−0.034 (0.483)
ISO—still air	22	1.37–7.28	2.17–4.14	0.078 (0.001)	−0.013 (0.396)
ISO—0.2 m/sec	7	2.23–9.17	2.02–3.90	−0.041 (0.430)	−0.046 (0.311)
ISO—1.0 m/sec	7	2.01–10.10	2.01–9.77	−0.033 (0.355)	−0.013 (0.646)

DISCUSSION

Although more research is needed to discern the relative effects of different factors that can contribute to sampler bias, these results suggest that physical factors such as particle shape and density have a more pronounced effect on sampler bias than environmental factors such as wind speed. Furthermore, the cyclone/IOM bias ratio is more pronounced than the cassette/IOM bias ratio for all conditions tested. It might be expected that the cyclone/IOM bias ratio is largely affected by the cyclone sampler bias that in turn is influenced by the inherent difference between the cyclone's collection efficiency curve and the curve associated with the respirable definition used to formulate the expected ratio, $E_{R/I}$.

The efficiency curve of the particular cyclone used in the study has been characterized in two separate studies conducted at different flow rates.[9,26] The work by Harper et al.[26] is used by the manufacturer to indicate the actual collection efficiency curve of the device and includes a "bias map" that gives the relative difference of the cyclone to that of a sampler exactly following the respirable definition over a wide range of d_g and σ_g values. Therefore, some undersampling or oversampling relative to the respirable definition can be expected when using this device. However, given the range of d_g and σ_g values (Table II), a slight oversampling (5–10%) should be expected rather than the undersampling observed. This conclusion presumes that the IOM was not oversampling relative to the inhalable curve, which is reasonable given the high collection efficiency expected over the range of relatively small d_g values obtained during this study.

As expected, the bias ratio values did not significantly change with a change in median aerosol size except when sampling the ISO dust in the still-air chamber. This result suggests that, for almost all conditions that involve the same aerosol in the same environmental conditions, the bias ratio value will be consistent despite changes in particle size. However, assuming that the IOM is collecting particles with its expected efficiency, a decrease in the cyclone/IOM bias ratio with a decrease in particle size suggests that the cyclone collects less particles as the aerosol size decreases. Given that the cut diameter of the instrument is 4 μm, this further suggests that small respirable particles that should otherwise pass through the cyclone to the filter are captured in the body of the cyclone, and at a higher rate as the percentage of respirable

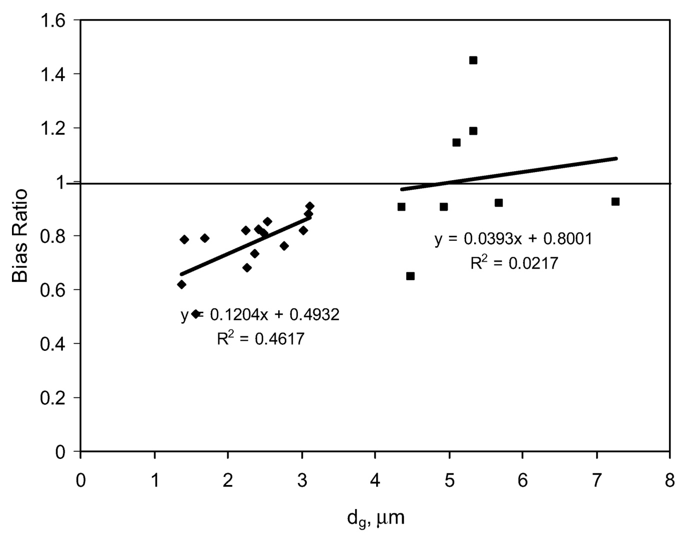

FIGURE 6. Bias ratio values for ISO dust in still-air chamber relative to mass median aerodynamic diameter, d_g

particles increases. The same phenomenon was not found when sampling the grain dust; however, only one grain trial had a d_g value less than 4 μm to prevent an assessment of this result with that dust type.

The method described here, involving the calculation of a bias ratio value to compensate for differences in the size distribution between settings where a sampler-to-sampler relationship is desired, relies on the use of concentration ratios rather than slope values to characterize the relationship. Linear regression analysis involves the development of a model that determines how and how well the level of a dependent variable is predicted by an independent variable. Whereas the calculation of a ratio as suggested here does not provide information as to whether the concentrations measured with one sampler can be used to predict the concentrations that would have been sampled by another sampler. Therefore, we suggest that a regression analysis be performed to test the association between the two samplers but that the concentration ratio and bias ratio value also be reported to aid other researchers for application in other similar occupational settings.

CONCLUSIONS

A number of studies have been performed to compare the aerosol concentrations measured by sampling devices with different collection characteristics. The motivation behind many of these studies is to provide information to other researchers who may be using any one of the samplers analyzed and wish to correlate those measurements with measurements made in the past with a different sampler. Rather than supply a slope or ratio comparing any two sampler types, we suggest that a bias ratio value also be reported that allows a compensation for changes in size distribution between that existing in the original study site and any subsequent site of interest. This information will result in a more accurate association between samplers used in the past and present. A series of laboratory trials simulating different flow conditions and with two different dust types demonstrated that in almost all the situations analyzed, the bias ratio value is independent of the median particle size. However these results also indicate that the bias ratio value may decrease with a decrease in particle size when comparing the SKC cyclone with the IOM sampler. These results suggest that, for most conditions, the size-distribution compensation can be applied to sampler-to-sampler correlations, provided that the original comparison was performed with the same dust type.

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