Evaluation Criteria for Bioaerosol Samplers

Journal:	*Environmental Science: Processes & Impacts*
Manuscript ID:	EM-ART-09-2014-000510.R2
Article Type:	Paper
Date Submitted by the Author:	12-Jan-2015
Complete List of Authors:	Kesavan, jana; US ARMY ECBC, Sagripanti, Jose-Luis; US ARMY ECBC,

Some Biological organisms and toxins in the environment have the potential to cause disease; therefore, aerosol samplers are employed to detect and quantify biological aerosols. Some of the important characteristics of aerosol samplers are: size, weight, air flow rate, sampling efficiency, power requirements, sampling mechanisms, output volume, etc. Even though there are many samplers available for an application, it is not easy selecting a sampler; therefore, this manuscript evaluates air sampler characteristics and describes a method for selecting appropriate air samplers for sampling infectious organisms and toxins.

Evaluation Criteria for Bioaerosol Samplers

Running Title: Bioaerosol Sampler Selection Criteria

Jana Kesavan Ph.D.* and Jose-Luis Sagripanti Ph.D.

Edgewood Chemical Biological Center

Aberdeen Proving Ground, Maryland, USA

Correspondence: Jana Kesavan

U. S. Army Edgewood Chemical Biological Center

RDCB-DRI-A E5951

5183 Blackhawk Road

Aberdeen Proving Ground

Maryland 21010

e-mail:Jana.Kesavan@us.army.mil

Phone #: (410) 436 1819

Keywords: Aerosol Sampling, Bioaerosols, Sampler Selection

The project was funded by the Edgewood Chemical Biological Center, Aberdeen Proving Ground, Maryland.

The authors do not have any conflict of interest.

ABSTRACT (word count 197)

Humans contract a variety of serious diseases through inhalation of infectious aerosols. Thus, the importance of monitoring air for microbial, toxic, or allergic content is recognized in clinical, occupational, and biodefense arena. However, accurate monitoring of potentially contaminated environments can be hampered by selection of aerosol samplers with inadequate performance for the intended task. In this study, 29 aerosol samplers were evaluated based on their respective air flow, size, weight, power consumption, and efficiency in sampling particles in the respirable range. The resulting data demonstrates that sampling air flow and efficiency vary widely, and cannot be predicted from the physical characteristics of air samplers, and hence, that proper selection of air samplers should be more involved than shopping for a device based on the limited characteristics that are published. The findings are summarized in an approach to rationally select bioaerosol samplers for use in the monitoring of infection control and environmental biomonitoring. The presented data demonstrates that inadequate selection of air samplers could result in a failure to collect particles of interest and thus, underestimate the risk and provide a false sense of security in contaminated health care settings and environments contaminated with infectious or toxic aerosols.

INTRODUCTION (word count 2964)

Several major human infectious diseases are transmitted through aerosolized germs. These include bacterial diseases such as tuberculosis and inhalation anthracis, viral diseases such as influenza and chickenpox, and systemic mycosis like coccidioidomycosis and paracoccidioidomycosis[1-3]. Aerosolized toxins and allergens are also transmitted through air and produce adverse health effects. The use of bio-aerosol sampling equipment is an essential tool for the detection of these and other infectious organisms which are spread through the inhalation of contaminated air. The importance of collecting particles from air for the identification of airborne microorganisms has been recognized for many decades, but technical difficulties in the sampling of bioaersols with high efficiency hinder the performance of infection control programs.

Increasing interest in monitoring airborne germs in clinical settings as well as in military barracks, schools and other places where people congregate has spurred commercial interest in developing a variety of devices to sample bioaerosols [4]. Even though quantitative assessment of bioaerosols are important, detecting the presence of infectious organisms (qualitative) will be adequate in some settings, such as in a health care setting and battlefield environments. Presence of these organisms will require evacuation or decontamination of the contaminated area. Some analyses techniques such as immunoassay based hand held assays provide quantitative results immediately for further investigation of the threat.

Current air samplers are based on one or more well established aerosol collection mechanisms such as impaction, interception, diffusion, electrostatic attraction, and gravitational

settling. Despite substantial design differences, all air samplers show some of the basic features such as inlet, pre-separator, ducts, aerosol concentrators, and collectors as shown in Figure 1. Each aerosol sampler has an inlet through which the aerosol enters the sampler. Many inlets are simply a tube open to the air, while inlets in some devices are more complex, having a "hat" to protect from rain, a "bug screen" to exclude insects and debris, and/or a pre separator to remove unwanted large particles. Obviously, rain hats are unnecessary in samplers intended for indoor applications. Pre-separators prevent the sampler from clogging and therefore, this feature is included in samplers intended to operate in environments that contain large particles in high concentrations. A second component of aerosol samplers, the transmission region, can also be either a simple tube connecting the inlet to the collection site, or more complex with aerosol concentrators, bends, constrictions, and expansions. Low concentrations of aerosolized microbes may call for the use of samplers with aerosol concentrators in the transmission region that concentrate the aerosol into a smaller volume of air. In a typical sampler, concentrated aerosols move from the transmission line into the aerosol collection region where particles are collected in a filter, impaction surface, cyclone, or agar plate [5-6]. Particles are collected on filters by impaction, interception, and diffusion collection mechanisms. Large particles are collected more efficiently by inertia of the particles in devices that contain impactors and cyclones. Small particles are collected more efficiently using diffusion and electrostatic attraction mechanisms.

Manufacturers make great efforts to design their samplers for maximum efficiency because every component in an aerosol sampler is a compromise between desirable characteristics and the additive reduction in sampling efficiency associated with losses at each additional component of the sampler. The overall efficiency of a device depends heavily on the

aerodynamic size of the target particle and is the result of particle losses during aspiration in the inlet, transmission, and final capture onto filters, agar plates, liquids, etc. Each additional stage results in some loss of particles, but in a well-designed, well-fabricated system, the losses in each of the sampler's individual components are low and hence, the overall sampling efficiency of the device remains high. In poorly designed and manufactured products, the sampling efficiency can be lowered by losses at one or more interface, back pressure buildup, or even through leaks.

In addition, the overall efficiency of a bioaerosol sampler is affected by how well particles are retained by the device during long sampling times, since particles in the collection fluid can escape back into the air (re-aerosolization) and be ejected with the exhaust [7]. The efficiency with which collected particles are ultimately delivered for the successful detection is also affected by the design and materials chosen by the manufacturer of the device as many organisms can adhere to certain materials in the walls of some samplers. In addition, when the subsequent analysis involves viable organisms, the apparent efficiency of the device may be lowered if some or all microorganisms in the aerosol particles are partially (or totally) inactivated during or after a harsh collecting process. Although molecular analysis can still establish whether infectious organisms were present in the collected air, even after rather severe degradation through the collecting process, the results from molecular analysis do not differentiate the dead organisms from those viable and hence infectious. In addition to the properties of the sampler, the characteristics of the airborne target organisms, particularly particle size, density, electrostatic charge and hardness of the targeted microbe heavily affect the sampling efficiency of a bioaerosol sampling system. Considering that failing to detect the presence of infectious agents provides a false sense of security; selection of appropriate

bioaerosol samplers having adequate sampling efficiency of aerosolized microorganisms or toxins in the desired particle size range is a fundamental consideration in the success of any project involving bioaerosols.

Many studies have evaluated a limited number of aerosol samplers used in occupational settings [8-12] and bioaerosol contaminated settings[13-15]. These studies focused on particular applications and evaluated very similar aerosol samplers in each study. A study by Fabian et al.[13] evaluated samplers for influenza virus detection and evaluated an SKC Biosampler, compact cascade impactor, Teflon filters, and gelatin filters. Xu and Yao[15] investigated biological collection efficiencies and culturable bacterial and fungal aerosol diversities using Reuter centrifugal sampler, Biosampler, electrostatic sampler, gelatin filter, BioStage impactor, mixed cellulose ester filter and gravitational settling methods. The improvement in sampling efficiency using mineral-oil-spread agar plates in Andersen six-stage sampler and BioStage impactor were studies by Xu et al.[14]. Overall, the major focus of these studies was to select the sampler with the best sampling efficiency; however, in biodefense related sampling situations, other sampler characteristics such as power requirements, noise, battery life, size and weight become a consideration in selecting samplers.

The goals of this study were to evaluate characteristics of a large segment of available aerosol samplers toward advancing a rational for selection of the products most adequate for particular applications in monitoring and controlling infectious diseases.

METHODOLOGY

Aerosol samplers were obtained by direct purchase or received for testing and evaluation by the Department of Defense during a period of seven years (2000 - 2006) [5, 7, 16-32]. Some of these samplers were breadboard devices which were improved over time and may be significantly different from the current commercial system. After unpacking, the weight and dimensions of each aerosol sampler were determined and each device was operated according to the manufacturer's instructions. A variety of air flow meters covering an ample range of air flows (Kurz Instruments, Monterey, CA; TSI Mass Flowmeter 4040, TSI Inc. Shoreview, MN) were employed to measure a wide range of air flow rates observed in this study.

The methodology for determining sampling efficiency is provided in detail in many of our published work; however, it is also briefly described below [5, 7, 31]. The experimental measurement of the sampling efficiency of every device was conducted in a 64 m^3 aerosol chamber maintained at an indoor temperature ranging from 20 to 23^oC. The sampling efficiency of all samplers was determined using inert materials such as aluminum oxide and fluorescent particles. In addition, the sampling efficiency of three samplers (EULSI, XMX/2A, and BioBadge) were also determined using biomaterials such as single spores of *Bacillus atrophaeus* var.*globigii* (BG), generated with a sonic nozzle and/or spore clusters of BG generated with an Ink Jet Aerosol Generator (IJAG, Edgewood Chemical Biological Center, MD)[5]. Inert aluminum oxide particles were aerosolized using a sonic nozzle (US Army ECBC, Aberdeen Proving Ground, MD). Inert fluorescent particles were generated by either a Collison nebulizer (BGI Inc., Waltham, MA), or a vibrating orifice aerosol generator (TSI Inc., Shoreview, MN). Sensitive bacteria can be killed during aerosol generation and sampling by shear forces and desiccation; therefore, a hardy spore forming bacteria spore such as BG was used in aerosol

studies. Bioparticles were generated by an IJAG, or a sonic nozzle. All aerosols were generated and mixed inside the chamber from which the devices under test and two to three reference filters simultaneously sampled the aerosol. The solid aluminum oxide particles were quantified using a Coulter Counter (Beckman Coulter, Inc., Brea, CA). The fluorescent particle concentration was measured by a Fluorometer (Model 450, Barnstead/Thermolyne Corporation, Dubuque, IA) and the collected bioparticles were enumerated by culturing and counting colonies. Biological samples were cultured after diluting and plating 100 μL of sample onto tiyptic soy agar plates and incubating (37°C for BG) overnight to obtain bacterial colonies [colony forming units (cfu)]. The sampling efficiency of each sampler (η) was determined by the equation:

$$\eta = \frac{\left(\frac{N_c}{V_s}\right)}{C_{air}} \times 100$$

where N_c is the number of organisms or particles collected and counted from a volume of air sampled, Vs (in liters), and C_{air} is the concentration of organisms or particles in air (cfu or particle number per Liter). The fluorescence readings were directly related to particle number and hence were used in calculations when these particles were aerosolized. The actual concentration of organisms or fluorescent particles in air was determined simultaneously by sampling air into reference filters quantified in parallel with each tested device. The concentration of microorganisms or inert particles obtained in the reference filters was considered as the true aerosol concentration (C_{air}) as the filters collect 100% of the particles and full recovery of the collected particles are obtained using the recovery procedure described in Kesavan et al.[5]. Briefly, membrane filters containing aluminum oxide and fluorescent PSL microspheres were placed into 50 mL centrifuge tubes containing 20 mL of Coulter Counter

solution or deionized water and vortexted for 5 min followed by hand shaking for 30 seconds to remove particles from filters for Coulter Counter or fluorometer analysis. Glass fiber filters containing fluorescent oleic acid particles were place in 50 mL centrifuge tube containing 20 mL of recovery solution and shaken on a rotator table (Lab-Line Instruments, Inc., Melrose Park, IL) for 15 min to remove the fluorescent material from the filter into the liquid for analysis by a fluorometer (Sequoia Turner Model 450 Fluorometer, Barnstead/Thermolyne Corporation, Dubuque, IA).The recovery solution is a mixture of de-ionized water and isopropyl alcohol (1:1) that was pH corrected to be between 8 and 10 using ammonium hydroxide. Glass fiber filters containing bacteria spores were placed in 50 mL centrifuge tube with 20 mL of phosphate buffered saline (PBS) with 0.01% Triton X-100 and vortexed for disintegration of the filters for cfu quantification using plating method.

Since infectious organisms have been shown to vary in the aerodynamic size [33-34] with size severely affecting sampling efficiency, we experimentally determined the sampling efficiency of samplers for aerosol particles with sizes between 1 and 10 μm. In general, at least three repetitions were conducted at each particle size. The actual particle size of aerosolized test particles was determined with an aerodynamic particle sizer (Model 3321, TSI Incorporated, Shoreview, MN).

RESULTS

The model and manufacturer of the 29 samplers studied here are presented in Table 1 with the devices broadly grouped according to their respective principle of collection. Each sampler was weighed and dimensions measured before measuring their respective air flows in

our aerosol chambers with the results presented in Table 2. The weight and dimensions indicated by the manufacturers (presented *in italics* in the table) of all samplers agreed well with our measurements. We evaluated whether the general assumption that higher sampling flow rates are delivered by bulkier and heavier samplers. Although heavier and larger samplers tended to provide higher sampling flow rates, this general assumption was not supported by the data presented in Figure 2. One-quarter of the samplers (7 out 29 samplers or 24%) had a performance outside the central regression line between weight (or size) and sampling flow rate.

Negligible differences (< 5%) between measured air flow and that specified by the manufacturers (*in italics* in Table 2) were obtained for 18 of the 29 samplers. Air flows > 5% were measured in 11 devices with 3 of these samplers having flow rates that differed between 5% and 10% from those specified by the manufacturer's brochures. One of the samplers produced an air flow of 14% lower than specified and EULSI and SASS 2000 resulted in airflows 36% and 16% higher, respectively, than the nominal air flow specified by their respective manufacturers.

Considering the strong dependence between sampling efficiency and particle size, we exposed samplers to aerosols in specific calibrated particle sizes ranging from 1 $\pm$ 0.1 µm to 10 $\pm$ 0.4 µm, since infectious particles in this range readily reach the lungs [4]. The efficiency of each aerosol sampler as a function of particle size had a distinctive shape. Since diverse curves could not be easily compared, we selected the average of the efficiencies observed during sampling of particles with aerodynamic diameters of 1 µm, 3 µm and of 5 µm. A direct comparison between samplers thus could be achieved by comparing the 1-3-5 µm average efficiencies as presented in Table 2. The results of samplers' efficiency varied from as high as 93% to as low as 14%,

demonstrating that some samplers may collect and recover the majority of germs aerosolized in particles of inhalation size while others will fail to detect the same risk.

We then investigated whether devices that are larger and heavier, although not always able to aspirate larger volumes of air (as shown in Figure 2), were associated to higher sampling efficiencies with the results presented in Figure 3. The scatter of data in Figure 3 indicates a weak negative correlation between sampling efficiencies and air flow (coefficient of determination of $R^2 = 0.14$ for all samplers). It can be observed in Figure 3 that samplers with low air flow rates (<34 Lpm) tend to have higher sampling efficiencies (>40%) compared to the higher air flow (>350 Lpm) samplers. It appears that the collection mechanisms have a strong effect on the sampling efficiency of medium air flow samplers. The correlation between sampling efficiencies and particle size was also low (coefficient of determination of $R^2 = 0.06$, data not shown).

Thus the variable sampling air rates and relatively unrelated sampling efficiencies measured for each device require the combination of these two parameters in order to determine each individual sampler performance (π) calculated as $\pi = f \times \eta$ where f is the sampling air flow rate and η is the average efficiency in the respirable size range of the device.

Lack of a strong correlation between weight (or size), sampling airflow, and sampling efficiency prevented the development of a straightforward analytical criteria for selection of air samplers based upon any one of these properties. Alternatively, the wide variation in characteristics and performance that we observed resulted in the decision tree proposed in Figure 4. The first requirement frequently encountered is whether aerosol sampling is to be made

outdoors or indoors. Although these two applications share some similar preferences, like selecting samplers with the highest π (the product of efficiency by flow rate of the device) or generally being smaller and lighter devices more desirable (see Figure 4), outdoor and indoor application also favor different characteristics. Samplers to be used outdoors require a rain "hat" and a "bug screen", as discussed in Introduction, while these features are less critical indoors. If air sampling will be outdoors, the sampler needs to have also a pre-separator built in the inlet section to prevent rain, insects or large particles from entering and clogging the sampler. Indoor air sampling generally does not require these measures. Noise is usually a major consideration indoors, but generally of secondary importance outdoors. Air sampling in dry and/or hot environments will evaporate liquid and in cold climates will freeze liquid collection media or agar plates, if the design of the device does not counter these climatic effects. Because of desiccation or freezing, sampling outdoors during times longer that a few hours need to be collected in a dry form that would assure persistence of biological or toxin specimens. In contrast, sampling indoors generally affords samples in either wet or dry form. In our experience, sampling outdoors, especially in remote areas, tend to require devices that are able to collect aerosols for extended periods, in a set-and-forget fashion. In contrast, indooor sampling tends to require shorter time periods due to the relatively finite air volume within building structures, and ready access allows closer monitoring of sampling performance. These differences almost always dictate that aerosol samplers used outdoor be powered by batteries, while indoor samplers benefit by AC powering from the electrical supply line. If portability into remote areas is required, then minimal weight that correlates with size, electrical power consumption and usually also with sampling airflow will be the determining factor.

Sample analysis methodology will also dictate the collection media where culture methodology requires gentle collection in liquid media while PCR analysis does not require culturable organisms. The schematic in Figure 4 does not intend to include an exhaustive list of all characteristics possible in air samplers nor guidelines for every potential operational requirement. Instead, Figure 4 is presented as a general guidance resulting from our own experience and the questions that we have received during decades from numerous institutions and commercial enterprises. A focus of this manuscript was assisting the selection of air samplers for biodefense applications. Thus, the characteristics evaluated were also of particular relevance in biodefense. In addition, aerosol samplers are also employed for determining exposure risk assessment and the majority of the samplers studied in this work can be easily employed for this purpose. In addition to the fundamental characteristics analyzed in this study, selection of air samplers for exposure risk assessment may also include additional characteristics such as portability, low noise level, and others too specific to particular applications as to be analyzed here

DISCUSSION

Identifying the purpose of sampling and the subsequent analysis methods must be carefully established since these requirements will dictate the selection of an adequate sampler. Specific applications will require certain “environmental characteristics” of the sampler that will impact the sampler selection as listed in Figure 4. These design characteristics are all important but not sufficient to assure the desired performance in aerosol sampling.

In many cases the sampler air flow rate has been the first consideration during selection of an aerosol sampler among all available products in the market. The data that we obtained did not support a direct correlation among key design characteristics and device performance among the 29 aerosol samplers. Size, weight and even sampling air flow rate were not predictive of particle sampling efficiency and thus overall performance. These findings highlight the need for a careful evaluation and judicious selection of aerosol samplers, involving multiple and simultaneous decisions on numerous variables associated to the device design and performance. At least as important as the flow rate delivered by a device is its sampling efficiency as this parameter can range from 15% to 93% (see Table 2) and affect the amount of collected particles (calculated as in $\pi = f \times \eta$ above) . After the combined consideration of air flow and sampling efficiency, final thoughts should be given to the interaction among power requirements, collection media, and sampling duration as related to the environmental conditions required in which sampling will occur.

This evaluation framework is important because the data presented in Figure 3 demonstrate that some aerosol samplers of the desired size and required environmental conditions may still fail to collect bioaersols within inhalation size range (see samplers corresponding to data points at the lower part of the graph in Figure 3). Sampling efficiency is the primary goal, therefore, the sampler selection must be reached after judicious analysis of the air flow and efficiency of the prospective devices, even when weight and size are of relevance in the specific application (since a particular device of the perfect size and weight, having also a high advertised air flow may still fail to substantially sample bioaersols if the sampling efficiency in the desired size range is low).

If weight (and associated size) is relatively unimportant, such as in many indoor applications, then a device that has the largest air flow and collects at the highest efficiency will likely have the highest chance of success in sampling airborne chemical or biological particles in air at relatively low concentrations. In contrast, if a device of relatively small size and low weight is desired, then a weight/efficiency analysis must be undertaken to identify the device with the combination of parameters assuring a higher chance of sampling airborne targets. The data presented above demonstrates that samplers of similar size and weight operating during a similar time period in an environment with similar concentration of aerosol particles, will collect different numbers of airborne particles. For example, Midget Impinger and the BioSampler weigh less than 1 kg and also have similar physical dimensions, but sample with considerably different airflow rates, 1 and 12.5 Lpm, respectively. The measured sampling efficiencies were also different (47% for Midget Impinger and 91 % for the BioSampler). Therefore, these devices operating under similar conditions, i.e. 100 CFU/L of air during 10 hours per day, (by assuring proper supply of electricity/batteries), would result (calculated as $\pi = f \times \eta$, see Result section above) in 28,200 collected organisms by the Midget Impinger and 682,500 collected organisms by the BioSampler. In the case of bioaerosol sampling, the sampled organism ratio of 1:24 between the Midget Impinger and the BioSampler respectively shows that the one of the samplers is significantly more (24-fold) efficient in collecting organisms compared to the other comparable device, highlighting the need for careful selection of aerosol samplers in most applications.

Many other studies have also been conducted to compare samplers for use in various applications[8-15]. Samplers selected for testing in theses studies were based on each application and requirements such as comparing to the inhalability criterion[8], sampling in high dust conditions, in windy conditions[9], directional sampling, sampling for specific materials[13] (dust, bacteria, viruses), requiring high sampling efficiency[14], high culturability, and based on analysis methods. For example, Sleeth and Vincent [8] compared the performances of four personal inhalable aerosol samplers at ultra-low wind speeds. The sampling efficiency of these samplers for 9 to 90 μm particles was compared to the inhalability criterion. In addition, Kauffer et al.[10] evaluated five aerosol samplers in wood industry by gravimetric analysis and determined the sampler with the highest efficiency. Comparing samplers for sampling bioaerosols have been conducted by many researchers. Xu and Yao[15] tested six samplers with various filters to determine the best aerosol sampler and the sampling parameters for obtaining the highest airborne bioaerosol biodiversity for health-related investigations. In addition, Reynolds et al. [9] evaluated the performance of four aerosol samplers in agricultural livestock environments and showed that wind speed and type of dust affect the performance of the samplers. Further, Fabian et al.[13] evaluated four aerosol samplers for detecting of airborne influenza virus using molecular and infectivity assays. The outcome of these studies showed that the sampling efficiency is the primary selection factor.

CONLCUSION

This study summarizes the analysis of 29 aerosol samplers, providing a criterion to select appropriate samplers for particular requirements. The data presented demonstrates that sampling

efficiency cannot be predicted from the physical characteristics of air samplers, and hence, that proper selection of air samplers should be more involved than just shopping for a device based on the limited characteristics provided by the manufacturers. The presented data demonstrates that improper selection of air samplers could result in a failure to collect organisms or toxins in the respirable range and thus underestimate the true risk, creating a false sense of security under circumstances that could result in unnecessary loss of life as in contaminated health care settings, or in other environments that are accidentally or purposely contaminated with infectious or toxic aerosols.

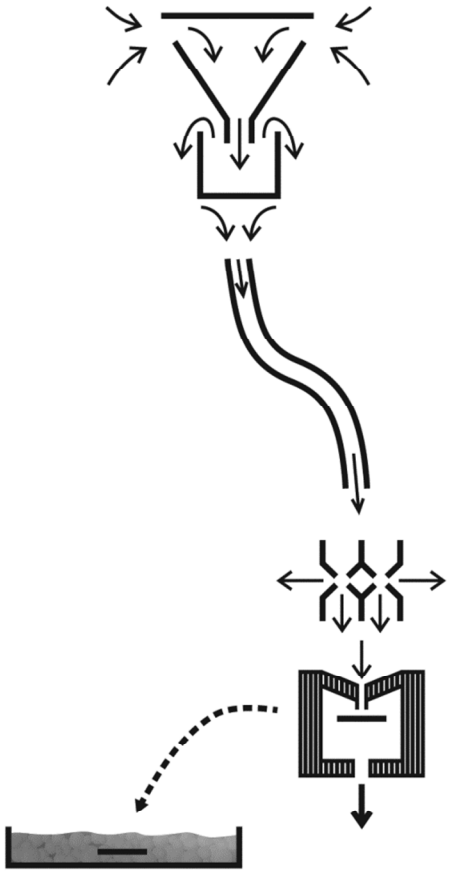
REFRERENCES

1. F. H. Top and P. F. Wehrle, *Communicable and Infectious Diseases 7th Edition*, Mosby Press Company, Saint Louis, 1972.
2. P. R. Murray, E. J. Baron, M. A. Pfaller, F. C. Tenover and R. H. Yolken, *Manual of Clinical Microbiology*, American Society for Microbiology Press, Washington, D.C., 1999.
3. C. J. Hurst, G. R. Knudsen, M. J. Mclnerney, L. D. Stetzenbach and M. V. Walter, *Manual of Environmental Microbiology*, American Society for Microbiology Press, Washington, D.C., 1997.
4. W. C. Hinds, *Aerosol Technology:Properties, Behavior, and Measurement of Airborne Particles*, John Wiley & Sons, Inc., New York, 1998.
5. J. Kesavan, J. R. Bottiger and A. R. McFarland, *Journal of Applied Microbiology*, 2008, 104, 285-295.
6. J. Brockmann, in *Aerosol Measurements: Principles techniques and Applications*, eds. K. Willeke and P. A. Baron, Van Nostrand Reinhold, New York, 1993, ch. 6, pp. 77-111.
7. J. Kesavan, D. schepers and A. R. McFarland, *Aerosol Science and Technology*, 2010, 44, 817-829.
8. D. K. Sleeth and J. H. Vincent, *Ann. Occup. Hyg.*, 2012, 56, 207-220.
9. S. J. Reynolds, J. Nakatsu, M. Tillery, T. Keefe, J. Mehaffy, P. S. Thorne, K. Donham, M. Nonnenmann, V. Golla and P. O'Shaughnessy, *Ann. Occup. Hyg.*, 2009, 53, 585-594.
10. E. Kauffer, R. Wrobel, P. Gorner, C. Rott, M. Grzebyk, X. Simon and O. Witschger, *Ann. Occup. Hyg.*, 2010, 54, 188-203.
11. A. D. Jones, R. J. Aitken, J. F. Fabries, E. Kauffer, G. Liden, A. Maynard, G. Riediger and W. Sahle, *Ann. Occup. Hyg.*, 2005, 49, 481-492.
12. P. Gorner, R. Wrobel, V. Micka, V. Skoda, J. Denis and J.-F. Fabries, *Ann. Occup. Hyg.*, 2001, 45, 43-54.
13. P. Fabian, J. J. McDevitt, E. A. Houseman and D. K. Milton, *Indoor Air*, 2009, 19, 433-441.
14. Z. Xu, K. Wei, Y. Wu, F. Shen, C. Q., M. Li and M. Yao, *PLOS ONE*, 2013, 8, 1-10.

15. Z. Xu and M. Yao, *Aerosol Science and Technology*, 2011, 45, 1143-1153.
16. J. Kesavan, J. Bottiger and R. Doherty, *Performance Characterization Methods of Aerosol Samplers*, US Army Edgewood Chemical Biological Center, Aberdeen Proving Ground, Maryland., 2005.
17. J. Kesavan and K. A. Hottell, *Characteristics and Sampling Efficiency of BioGuardian air sampler*, 2003.
18. J. Kesavan and K. A. Hottell, *Characteristics and Sampling Efficiency of Aerosol Samplers Manufactured by MesoSystem Technology, Inc.*, 2003.
19. J. Kesavan and K. A. Hottell, *Characteristics, sampling efficiency, and possible improvements to the aerosol to liquid particle extraction system (ALPES)*, 2004.
20. J. Kesavan and K. A. Hottell, *Characteristics and sampling efficiencies of two BioGuardian 12.03 aerosol samplers*, 2005.
21. J. Kesavan and K. A. Hottell, *Characteristics and sampling efficiencies of four biobadge aerosol samplers*, 2005.
22. J. Kesavan, K. A. Hottell and D. Schepers, *Characteristics and sampling efficiencies of Smart Air Sampler System, SASS 2000 plus*, 2004.
23. J. Kesavan, D. Jones, D. Carlile, T. Sutton and R. Doherty, *Sampling efficiency of aerosol samplers: rotating arm sampler, BioCapture, and Microvic*, 2002.
24. J. Kesavan and D. Schepers, *Characteristics and sampling efficiency of eight unit linear slot impactor (EULSI)*, 2006.
25. J. Kesavan and D. Schepers, *Characteristics and sampling efficiencies of MicroST virtual impactors*, 2006.
26. J. Kesavan and D. Schepers, *Characteristics and sampling efficiencies of SpinCon and pre-production Omni model aerosol samplers*, 2006.
27. J. Kesavan and D. Schepers, *Characteristics and sampling efficiencies of Omni 3000 aerosol samplers*, 2006.
28. J. Kesavan and D. Schepers, *Characteristics and sampling efficiencies of portable high throughput liquid-assisted aerosol sampler model APAS-2 (PHTLAAS-APAS-2)*, 2007.
29. J. Kesavan, D. Schepers and J. Bottiger, *Characteristics of twenty nine aerosol samplers tested at Edgewood Chemical Biological Center*, Report ECBC-TR-822, Edgewood Chemical Biological Center, Aberdeen Proving Ground, Maryland, 2011.
30. J. Kesavan, D. Schepers, T. Sutton, P. Deluca, M. Williamson and D. Wise, *Characteristics, Sampling Efficiency, and Battery Life of Smart Air Sampler System (SASS) 3000 and SASS 3100.*, Report ECBC-TR-824, 2010.
31. J. Kesavan and E. Stuebing, in *Atmospheric and Biological Environmental Monitoring*, eds. Y. J. Kim, U. Platt, M. B. Gu and H. Iwahashi, Springer, New York, 2009.
32. J. Kesavan, T. Sutton, K. A. Hottell and R. Doherty, *Characteristics and sampling efficiency of PHTLAAS air sampler*, 2002.
33. M. Carrera, J. Kesavan, R. Zandomeni and J. L. Sagripanti, *Aerosol Science and Technology*, 2005, 39, 960-965.
34. M. Carrera, R. O. Zandomeni and J. L. Sagripanti, *Journal of Applied Microbiology*, 2007, 102, 303 - 312.

LIST OF ILLUSTRATIONS

LIST OF TABLES



EXAMPLE COMPONENTS	Type of Efficiency
Inlet	Aspiration Efficiency
Pre-separator	Transmission Efficiency
Ducts	Transmission Efficiency
Aerosol Concentrator	Transmission Efficiency
Collector	Collection Efficiency Retention Efficiency
Sample Extraction	Recovery Efficiency

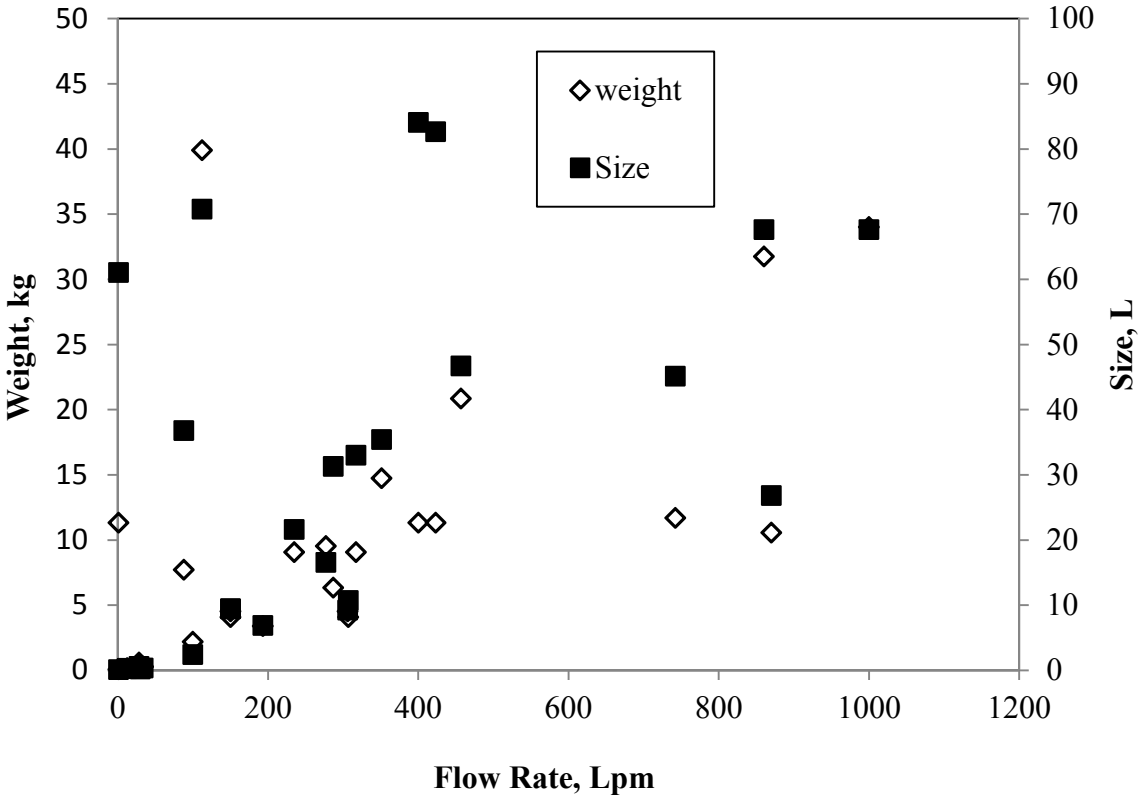

weight
Size
Weight, kg
Size, L
Flow Rate, Lpm
0
5
10
15
20
25
30
35
40
45
50
0
10
20
30
40
50
60
70
80
90
100
0
200
400
600
800
1000
1200

Figure 2

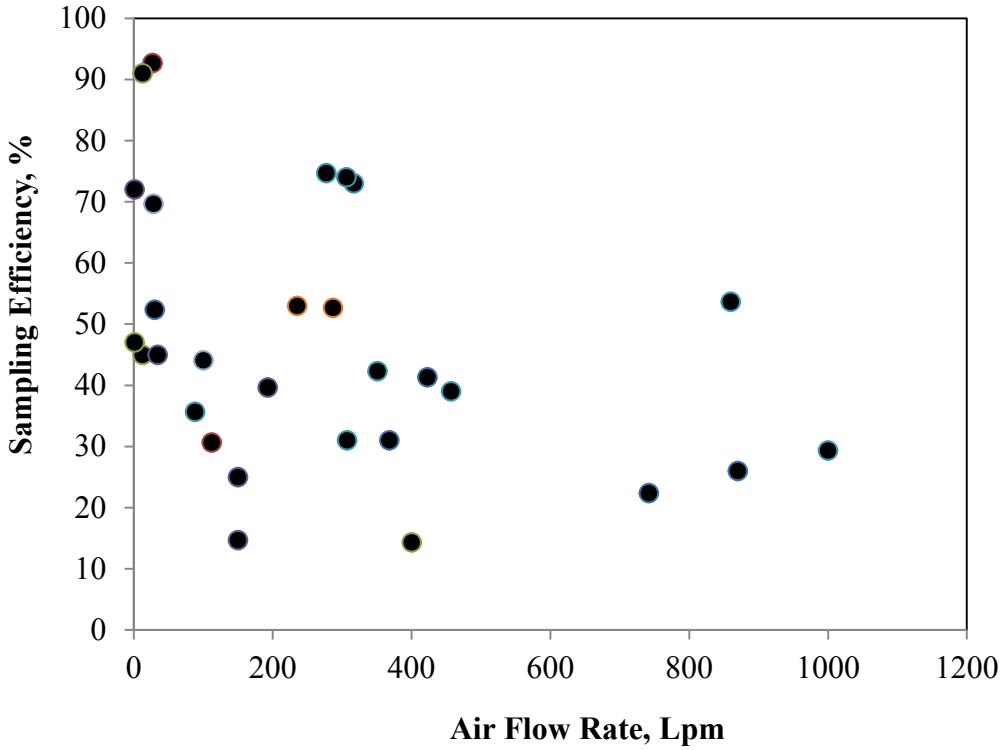

Sampling Efficiency, %
100
90
80
70
60
50
40
30
20
10
0
0
200
400
600
800
1000
1200
Air Flow Rate, Lpm

Figure 3

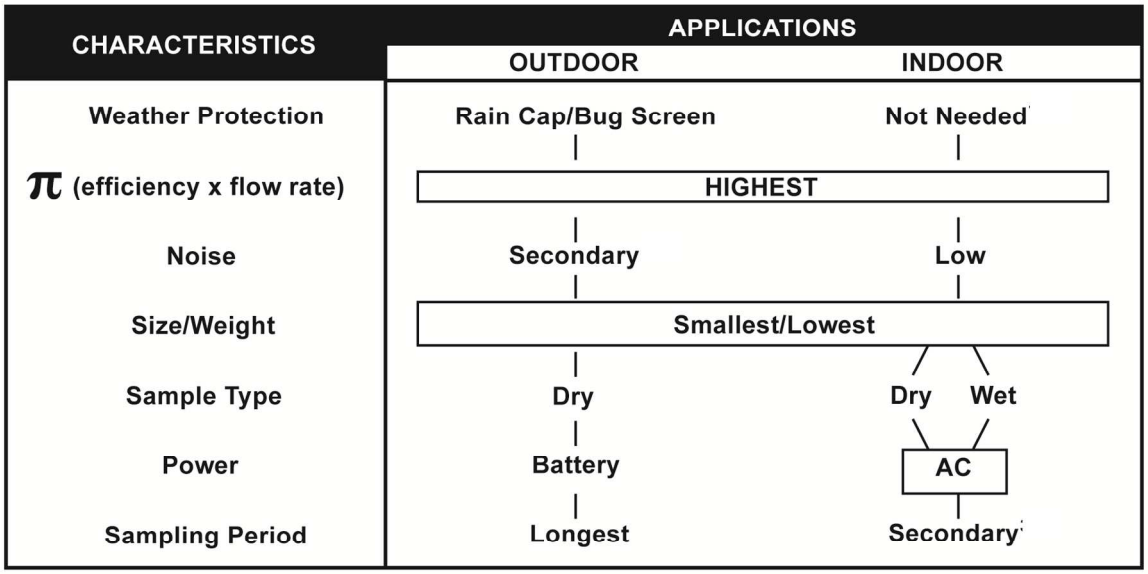

CHARACTERISTICS
APPLICATIONS
OUTDOOR
INDOOR
Weather Protection
Rain Cap/Bug Screen
Not Needed
π (efficiency x flow rate)
HIGHEST
Noise
Secondary
Low
Size/Weight
Smallest/Lowest
Sample Type
Dry
Dry
Wet
Power
Battery
AC
Sampling Period
Longest
Secondary

Figure 4

Sampler Name	Company Info	Collection Mechanism
	Aerosol Concentrators	
EULSI	Texas A & M University, College Station, TX	One stage aerosol concentrator*
One Stage Microvic	MesoSystems Technology, Inc., Kennewick, WA	
Two stage Microvic	MesoSystems Technology, Inc., Kennewick, WA	Two stage aerosol concentrator*
XMX/2A	Dycor Technologies Ltd., Alberta, Canada	Three stage aerosol concentrator*
Modified XMX		
	Filter Sampler	
Rotating Arm Sampler	US Army ECBC, Aberdeen Proving Ground, MD	Filter*
Met One (Sandia)	Sandia National Labs, Albuquerque, NM	
	Impingers	
AGI 30	Ace Glass Inc. Vineland, NJ	Impaction/Impingement into liquid§
Midget Impinger	SKC, Inc., Eighty-Four, PA	
BioSampler	SKC, Inc., Eighty-Four, PA	Gentle impaction onto liquid§
Two Stg Microvic & BioSampler	MesoSystems Technology, Inc., Kennewick, WA	Two stage concentrator w/ biosampler§
	Impaction onto a Surface	
AHTS	Texas A & M University, College Station, TX	Impaction onto wet surface§
BT 500, BT550, BT650	MesoSystems Technology, Inc., Kennewick, WA	Impaction onto wet/dry rotating surface§
BioBadge	MesoSystems Technology, Inc., Kennewick, WA	Impaction onto dry rotating surface§
	Cyclones	
PHTLAAS #3 & #4	Zaromb Research Corp., Hinsdale, IL	Wetted wall cyclone§
SASS 2000	Research International, Woodinville, WA	
SpinCon	Midwest Research Inst., Kansas City, MO	
Omni 3000	Sceptor Industries, Inc., Kansas City, MO	
BioGardan 1, 4, 12.2 & 12.3	InnovaTek Inc., Richland, WA	Dry cyclone with washing§
	Electrostatic Collection	
ALPES 1 & 2	Savannah River Technology Center, Aiken, SC	Electrostatic Collection§
	Collection onto Agar Plates	
One Stage Impactor	Thermo Anderson Inc., Smyrna, GA	Impaction onto a collection surface
MAS 100	EM Science, Gibbstown, NJ	Impaction onto an agar plate

*Sample on filters; §sample in liquid;

Sampler Name[1]	Flowrate[2] (L/min) Measured (*Specified*)	Weight kg (lbs)	Dimensions L×W×H(cm)	Sampling Efficiency 1 µm	3 µm	5 µm	Average 1-5 µm
Midget Impinger	**1.0** *(1.0)*	0.1 *(0.17)*	2.5×2.5×18.5	13	90	38	**47.0**
AHTS	**1.0** *(1.0)*	11.4 *(25.0)*	58.4×22.9×45.7	67	78	71	**72.0**
AGI 30	**12.5** *(12.5)*	0.1 *(0.29)*	3.8×3.8×27.4	27	49	59	**45.0**
BioSampler	**12.5** *(12.5)*	0.2 *(0.37)*	3.8×3.8×21.6	96	98	79	**91.0**
Rotating Arm Sampler	**27.0** *(27.0)*	227 *(500)*[3]	86.4×55.9×152.4	95	93	90	**92.7**
One Stage Impactor	**28.3** *(28.3)*	0.6 *(1.3)*	10.5×10.5×7.4	58	73	78	**69.7**
One Stage Microvic	**30.0** *(30.0)*	0.3 *(0.7)*	5.1×5.1×7.6	47	56	54	**52.3**
BioBadge	**34.0** *(35.0)*	0.3 *(0.6)*	15.2×7.6×5.1	6	63	66	**45.0**
BioGardan 1	**88.0** *(90)*	7.7 *(17.0)*	30.5×27.9×43.2	21	46	40	**35.7**
MAS 100	**100.0** *(100.0)*	2.2 *(4.85)*	10.9×10.9×26.2	7.3	59	66	**44.1**
Sandia Met-One	**112.0** *(NL)*[4]	40 *(88)*	61×83.8×78.7	13	12	67	**30.7**
BT 500	**150.0** *(150.0)*	4.1 *(9.0)*	30.5×15.2×20.3	11	20	13	**14.7**
BT 550	**150.0** *(150.0)*	4.5 *(10.0)*	30.5×15.2×20.3	25	27	23	**25.0**
BT650	**193.0** *(200.0)*	3.4 *(7.5)*	12.7×15.2×35.6	16	59	44	**39.7**
ALPES 1	**235.0** *(250.0)*	9.1 *(20.0)*[3]	55.9×15.2×25.4	49	53	57	**53.0**
Omni 3000	**277.0** *(300.0)*	9.5 *(21.0)*	21.6×17.8×43.2	43	91	90	**74.7**
ALPES 2	**287.0** *(NL)*	6.4 *(14.0)*	30.5×17.8×53.3	50	57	51	**52.7**
PHTLAAS #4	**306.0** *(NL)*	4.5 *(10.0)*	15.2×15.2×50.8	55	82	85	**74.0**
SASS 2000	**307.0** *(265)*	4.1 *(9.0)*	20.3×20.3×33	5	36	52	**31.0**
PHTLAAS #3	**317.0** *(NL)*	9.1 *(20.0)*	45.7×35.6×20.3	66	78	75	**73.0**
BioGardian 4	**351.0** *(350.0)*	14.8 *(32.5)*	30.5×25.4×45.7	34	48	45	**42.3**
EULSI	**368.0** *(270)*	227 *(500)*[3]	66×55.9×91.4	21	35	37	**31.0**
Two Stage Microvic w/ BioSampler	**403.0** *(400.0)*	11.4 *(25.0)*	48.3×22.9×76.2	15	18	10	**14.3**
Two Stage Microvic	**423.0** *(450.0)*	11.4 *(25.0)*	48.3×22.9×74.9	52	46	26	**41.3**
SpinCon	**457.0** *(450.0)*	20.9 *(46.0)*	38.1×25.4×48.3	47	56	14	**39.0**
XMX/2A	**742.0** *(800.0)*	11.7 *(25.8)*	21.6×45.7×45.7	0.1	40	27	**22.4**
BioGardian 12.3	**860.0** *(1000.0)*	31.8 *(70.0)*	38.1×38.1×63.5	48	60	53	**53.7**
Modified XMX	**870.0** *(900.0)*	10.6 *(23.3)*	45.7×17.8×33	20	28	30	**26.0**
BioGardian 12.2	**1000.0** *(1,100.0)*	34.1 *(75.0)*	36.8×36.8×63.5	27	32	29	**29.3**

1 The sampler information is provided as an example of the characteristics to consider in selection of a sampler for testing.

2 The flow rates presented are those measured in our laboratory and those specified by the manufacturers (*in italics*)

3 *Approximate values*

4 NL – not listed