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## COLLECTION OF THREE BACTERIAL AEROSOLS BY RESPIRATOR AND SURGICAL MASK FILTERS UNDER VARYING CONDITIONS OF FLOW AND RELATIVE HUMIDITY

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**Abstract**—A variety of respirator filters and surgical masks were challenged with three aerosolized bacteria: *Mycobacterium abscessus* (*M.a.*) (a rod), *Staphylococcus epidermidis* (*S.e.*) (a sphere), and *Bacillus subtilis* (*B.s.*) (a rod). Tests were conducted at two flow rates (45 and 85 l./min) and two humidity levels (30 and 70%). Aerosols were measured with a total-particle, direct-reading, spectrometer and a viable particle cascade impactor. Measurements up- and downstream of the filter or mask were used in determining aerosol penetration; respirator or surgical mask fit was not evaluated.

Bioaerosol penetration measured with two aerosol sampling instruments was found to correlate. Additionally, bioaerosol test parameters were evaluated with respect to their effect on penetration. Increasing flow resulted in increased penetration of all organisms while an increase in relative humidity did not exert a consistent effect on all organisms. Of the respirators approved by the National Institute for Occupational Safety and Health (NIOSH), filter efficiency was as expected with dust/mist respirators having the lowest and HEPA filters the highest efficiency. Surgical masks were the least efficient of all filters tested; these are not certified by NIOSH.

Bioaerosol penetration was compared to that of a polystyrene latex sphere (PSL) aerosol. Penetration of the test aerosols was predicted on the basis of particle aerodynamic diameter and was expected to be in this order: PSL > *M.a.* > *S.e.* = *B.s.* The PSL aerosol was the most penetrating, as predicted. However, results showed that *B.s.* was more penetrating than *S.e.* The aerodynamic diameter may not be the best parameter for predicting aerosol penetration of non-spherical particles in these filters. © 1997 British Occupational Hygiene Society. Published by Elsevier Science Ltd.

### INTRODUCTION

In the U.S., respirators are certified by the National Institute for Occupational Safety and Health (NIOSH) using non-biological aerosols chosen to represent those found in industrial workplaces. Recently, NIOSH-certified respirators have been suggested as a method for controlling exposures to infectious organisms in health care settings. It has not been documented that filter performance determined with non-biological aerosols is representative of filter performance when challenged with infectious aerosols.

Respirator certification employing infectious or other disease-causing aerosols is impractical due to the health risk associated with such aerosols and the difficulty of measuring living microorganisms. Rather, simplified tests can be designed using surrogate aerosols and expedient analytic methods. This research addresses these issues through a series of experiments which evaluated surgical mask and respirator

filter performance when challenged with both non-biological and biological aerosols, using instruments which measure total or culturable particles.

This paper describes the results of experiments in which respirator and surgical mask filters were challenged with three biological aerosols. The experimental objectives were:

- To evaluate bioaerosol penetration using both a total-particle, direct-reading detector and a viable aerosol sampler,
- To evaluate which experimental parameters influence bioaerosol penetration, and
- To compare the penetration of three bioaerosols with that of a non-biological aerosol.

'Aerosol' is defined as a dispersion system of solid or liquid particles suspended in a gas. If these particles contain or consist of microorganisms (i.e. bacteria, viruses, fungi, protozoa) or their by-products (i.e. endotoxins, mycotoxins) the aerosol is referred to as a 'bioaerosol.' The most common route of exposure for aerosols is the respiratory system and bioaerosols may range in particle size from  $< 5 \mu\text{m}$  to greater than  $100 \mu\text{m}$ . Bioaerosols may consist of cell fragments, single and multi-celled particles, droplets, and airborne dust and debris. Although most sources for bioaerosols are natural (humans, animals, plants, water, and soil), microorganisms are also used increasingly in biotechnology (Lacey and Dutkiewicz, 1994).

Health effects caused by biological aerosols can generally be classified into two types: allergenic and infectious (Griffiths and DeCosemo, 1994). Allergic reactions can be induced by the whole organism, a fragment of the organism or its by-product. Infections result when living organisms multiply in the host and cause disease. Several types of organisms can cause infection, including bacteria, viruses, and protozoa. Infectious diseases transmitted by the airborne route include tuberculosis, Legionnaires' disease, Q fever, histoplasmosis, coccidioidomycosis, mumps, measles, and influenza (Benenson, 1995).

Bacteria, the focus of this research, are single-celled prokaryotes (no nucleus) that make up the kingdom Monera. They are classified by their shape [bacillus (rod-like), coccus (spherical or ovoid) or spirillum (spiral or corkscrew)] or by the ability of the cell wall to accept a stain (Gram-positive, Gram-negative or acid-fast). The characteristics of bacteria which determine if exposure to an organism will cause disease are the genus and species, growth requirements, replication time, toxicity, and air concentrations. For bacteria in aerosols, the size, shape, density, and surface characteristics of the cell or particle are also relevant to exposure.

A variety of infectious bacteria may present inhalation hazards to workers in a number of occupations (Table 1) (Levy and Wegman, 1995; Benenson, 1995). Although respiratory protection is usually a temporary or 'last resort' measure for controlling inhalation hazards, there may be times when it is necessary. In health care settings, where people are frequently the source of infectious aerosols, other control methods are difficult to implement. For this reason, several U.S. government agencies, including the Centers for Disease Control and Prevention (CDC), NIOSH, and the Occupational Safety and Health Administration (OSHA), have recommended the use of respiratory protection to control worker exposures to *Mycobacterium tuberculosis*, the organism which causes tuberculosis (NIOSH, 1992; Clark, 1993; CDC, 1994).

Table 1. Occupationally-related airborne bacteria and associated disease (Levy and Wegman, 1995; Benenson, 1995)

Bacteria	Disease	Occupation
<i>Legionellae pneumophilia</i>	Legionnaire's	Maintenance worker
<i>Bacillus anthracis</i>	Anthrax	Farmer, butcher, meatpacker, renderer, veterinarian
<i>Brucella abortus</i> , <i>B. melitensis</i> , <i>B. suis</i> , <i>B. canis</i>	Brucellosis	Farmer, veterinarian
<i>Yersinia pestis</i>	Plague	Farmer, geologist, hunter
<i>Francisella tularensis</i>	Tularemia	Cook, farmer, fur handler, hunter
<i>Bordetella pertussis</i>	Whooping cough	Day-care worker, Healthcare worker
<i>Mycobacterium tuberculosis</i> , <i>M. bovis</i> , <i>M. africanum</i>	Tuberculosis	Healthcare worker, miner, laboratory worker

Currently, NIOSH does not use biological aerosols to certify respirators. Employing infectious bacteria to certify respirator filters would be impractical, for several reasons. Aerosolization of infectious bacteria is typically discouraged because of possible health hazards and the need for specially-designed facilities. Additionally, collection and analysis of biological aerosols are tedious compared to that of non-biological aerosols. To differentiate biological from non-biological aerosols the most common techniques employ viable sampling. This involves allowing collected organisms to replicate on a growth medium until the colonies can be counted. Only those organisms which are viable (able to replicate) are detected. While only viable organisms can cause infection, this method is not practical for filtration research because aerosolization, transport and sampling may damage the organism, reducing viability and therefore, detectability (Chatigny *et al.*, 1990).

This research was designed to evaluate methods for predicting filter performance with infectious aerosols, without actually employing such aerosols. Previous research with a single bacterial aerosol [*Mycobacterium abscessus* (*M.a.*)] demonstrated that non-biological aerosols may be an appropriate surrogate for predicting filter collection of biological aerosols (Brosseau *et al.*, 1997). Penetration of *M.a.* was measured using both a viable sampler and a total-particle, direct-reading detector; these two sampling techniques yielded similar measures of filter penetration for a wide range of filter media. Additionally, it has been found, for non-biological aerosols greater than 0.3  $\mu\text{m}$ , that an increase in volumetric flow results in an increase in penetration (Stevens and Moyer, 1989). This also occurred in experiments with *M.a.*, where penetration at 85 l./min was significantly greater than at 45 l./min (Brosseau *et al.*, 1997). Several particle collection mechanisms are a function of flow, therefore we expected penetration of the two bioaerosols employed in this research to be different at the two flow rates. However, since these bioaerosols were slightly larger than either the *M.a.* or those used by Stevens and Moyer (1989), we could not predict the direction in which the change would occur.

A direct comparison of biological and non-biological aerosol penetration is also presented. The penetration of each aerosol was predicted as a function of particle aerodynamic diameter ( $d_{ac}$ ). Aerodynamic diameter is defined as the diameter of the equivalent unit density sphere ( $10^3 \text{ kg/m}^3$ ) with the same settling velocity of the particle (Hinds, 1982). It is the particle size index most relevant to some (but not all) aspects of particle capture by filters (for example inertial, gravitational). For

particles with a  $d_{ae}$  greater than  $0.4 \mu\text{m}$ , an increase in  $d_{ae}$  results in a decrease in penetration (Stevens and Moyer, 1989). For particle sizes used in this research ( $> 0.5 \mu\text{m}$ ) we expected inertia and gravity to be the dominant capture mechanisms and therefore predicted that the aerosol with the smallest  $d_{ae}$  (that is PSL at  $0.55 \mu\text{m}$ ) would be the most penetrating.

The biological aerosols employed in these experiments were selected to represent a range of shapes and sizes typical of infectious bacteria. *Mycobacterium abscessus* (*M.a.*), an acid-fast bacillus, was chosen as a biological surrogate for *Mycobacterium tuberculosis*. *Staphylococcus epidermidis* (*S.e.*) is a spherical organism and *Bacillus subtilis* (*B.s.*) is a rod-shaped, spore-forming, organism. Consideration was also given to how resistant these organisms would be to variations in environmental conditions (that is humidity and temperature). For example, *B.s.*, a spore, was expected to be the most resistant to harsh environmental conditions, while *S. e.* was expected to be the least resistant organism.

#### METHODS

All surgical mask and respirator filter media were tested in an enclosed system which has been described in detail elsewhere (Brosseau *et al.*, 1994; Brosseau *et al.*, 1997). This system consists of a 6.5 in. diameter vertical steel tube in which the aerosol challenges the filter media. Aerosols were generated by nebulization and electrically neutralized to Boltzmann's equilibrium by passing through a Kr-85 charge neutralizer (TSI Inc., St. Paul, MN) before combining with dilution air. Aerosol was sampled up- and downstream of the filter, which was sealed into the system. All aerosols were measured using the Aerodynamic Particle Sizer (APS) (TSI, Inc., Shoreview, MN), a direct-reading particle counter and sizer (Wilson and Liu, 1980). Biological aerosols were also measured with a viable particle sampler. The Andersen six stage viable particle sampler ('Andersen') (Andersen/Graseby, Atlanta, GA) was modified by the addition of a seventh stage and dilutor to collect aerosols as small as  $0.45 \mu\text{m}$  and to sample at lower flows ( $1.5 \text{ l./min}$ ), if necessary (Andersen, 1958; McCullough *et al.*, in review). In all tests only the efficiency of the filter medium was tested; facepiece fit was not evaluated.

The non-biological aerosol tests employed a monodisperse, polystyrene latex sphere (PSL) aerosol,  $0.55 \mu\text{m}$  in diameter. Three replicates of 15 surgical masks and 75 NIOSH-certified respirator filters were evaluated at  $45 \text{ l./min}$  and 50% relative humidity. These experiments found a range of penetration within each filter certification category. The results of these tests have been described in detail elsewhere and will be used here for comparison with biological aerosol penetration (Brosseau *et al.*, 1997).

Filter media challenged with the three biological aerosols were preconditioned prior to testing at  $85\% \pm 5\%$  relative humidity for  $24 \pm 1 \text{ h}$ . The bacteria were aerosolized using a Collison nebulizer and testing of three replicates was carried out at two flow rates ( $45$  and  $85 \text{ l./min}$ ) and two conditions of relative humidity ( $30 \pm 5$  and  $70 \pm 5\%$ ) (McCullough *et al.*, in review; Brosseau *et al.*, 1997). Sixteen respirator filters from the three NIOSH approval categories were tested [eight dust/mist (DM) filters, six dust/fume/mist (DFM) filters, and two high efficiency particulate air (HEPA) filters]. By visual inspection it appeared that all but one pleated HEPA filter

relied at least partially on electrostatic forces for collection of particles. No quantitative assessment of electrostatic charge was attempted, however. Five surgical masks, which are not approved (NA) by NIOSH, were also tested.

*Mycobacterium abscessus* were obtained from the Centers for Disease Control and Prevention, Hospital Infections Laboratory (Atlanta, GA) for use in a preliminary study (Chen *et al.*, 1994). *Bacillus subtilis* subsp. *niger* spores were provided by the Life Sciences Division (MT-L) of the U.S. Army Dugway Proving Ground (Dugway, UT). *Staphylococcus epidermidis* was ordered from the American Type Culture Collection (Rockville, MD) (strain #14990).

Since particle aerodynamic diameter ( $d_{ae}$ ) was used to predict aerosol penetration, it was both estimated and measured for each aerosol (assuming a density of  $1 \text{ g/cm}^3$ ). The standard equation was used for *S.e.* (a sphere) (Hinds, 1982). Equations specific for rod-shaped and fibrous particles were used for *M.a.* and *B.s.*; these account for shape and orientation in the air (Cox, 1970; Burke and Esmen, 1978).

The estimated range of aerodynamic diameter was similar for all three organisms (Table 2); *M.a.* had a somewhat smaller mean measured  $d_{ae}$  than the other two biological aerosols. The PSL aerosol was expected to be the most penetrating of all the test aerosols, while *S.e.* and *B.s.* were expected to be the least penetrating.

Filter penetration ( $P$ ) was determined by the ratio of particles penetrating the filter (concentration downstream of the filter) to those available for challenge (concentration upstream of the filter). Prior to statistical analysis, the logit transformation was used to normalize the data:

$$\text{logit}(P) = \log(P/(100 - P)) \quad (1)$$

Comparisons of the two samplers and of biological and non-biological aerosol penetration of filters were performed using linear regression analysis. Those factors which were significant in predicting bioaerosol penetration were identified using analysis of variance (ANOVA) (Table 3). Tukey's multiple comparisons were employed to test for differences between levels of a statistically significant variable (Kleinbaum *et al.*, 1988).

## RESULTS

### *Comparison of instruments used to measure bioaerosol penetration*

Penetration of the three bioaerosols was measured using both the APS ( $P_{\text{APS}}$ ) and Andersen ( $P_{\text{AND}}$ ) instruments. These measurements were compared using linear regression analysis (Table 3). The two instruments were found to give equivalent results (Fig. 1):

$$\text{Logit}(P_{\text{AND}}) = 1.086(\text{Logit}P_{\text{APS}}); R^2 = 0.976$$

The least variability between the two instruments occurred when measuring in the mid-range of penetration (0.1–50%), that is for the DM and DFM filters (Fig. 1). The greater variability at the extreme penetrations is most likely due to lack of precision in the Andersen sampler in these ranges.

Table 2. Calculated and measured aerodynamic diameter ( $d_{ac}$ ) for three test bioaerosols

Organism	Physical dimensions, $\mu\text{m}$	For spheres <sup>2</sup>	Estimated $d_{ac}$ , $\mu\text{m}$ <sup>1</sup>		Measured $d_{ac}$	
			For rods <sup>3</sup>	For fibers <sup>4</sup>	APS (Mean number $d_{ac}$ , $\mu\text{m} \pm 1$ SD)	Andersen sampler <sup>5</sup> (Mean distribution by stage (%) $\pm 1$ SD)
<i>Mycobacterium abscessus</i>	length <sup>6</sup> : 1–4 width: 0.3–0.5	NA	$\parallel 0.37\text{--}0.97^a$ $\perp 0.33\text{--}1.15^b$	0.31–1.03	0.69 $\pm$ 0.03	5: 6.2 $\pm$ 6.7 6: 55.4 $\pm$ 20.5 7: 38.4 $\pm$ 19.8
<i>Staphylococcus epidermidis</i>	diameter <sup>7</sup> : 0.5–1.5	0.5–1.5	NA	NA	0.87 $\pm$ 0.04	4: 0.7 $\pm$ 2.6 5: 68 $\pm$ 13 6: 31.3 $\pm$ 14
<i>Bacillus subtilis</i>	length <sup>8</sup> : 2–3 width: 0.5–0.8	NA	$\parallel 0.86\text{--}1.0^a$ $\perp 1.0\text{--}1.1^b$	0.90–0.97	0.88 $\pm$ 0.03	4: 2.5 $\pm$ 5.4 5: 55 $\pm$ 12 6: 42.5 $\pm$ 11.2

NA = not applicable, SD = standard deviation.

<sup>1</sup> Density assumed to be 1 g/cm<sup>3</sup> (Dimmick, 1969).

<sup>2</sup> Hinds, 1982.

<sup>3</sup> Cox, 1970, <sup>a</sup> particle oriented parallel to flow; <sup>b</sup> particle oriented perpendicular to flow.

<sup>4</sup> Burke and Esmen, 1978.

<sup>5</sup> Stage 4: 2.1–3.1  $\mu\text{m}$ , stage 5: 1.1–2.1  $\mu\text{m}$ , stage 6: 0.65–1.1  $\mu\text{m}$ , stage 7: 0.45–0.65  $\mu\text{m}$  (Andersen, 1958; McCullough *et al.*, in press).

<sup>6</sup> Runyon *et al.*, 1974.

<sup>7</sup> Baird-Parker, 1974.

<sup>8</sup> Gibson and Gordon, 1974.

Table 3. Description of the statistical analyses

Hypothesis	Analysis	Independent variable	Dependent variables	Conditions	Number of replications
$P_{AND} = P_{APS}$	Regression	$P_{AND}$	$P_{APS}$	21 filters with 4 approvals, 2 flows, 2 RH	3 per condition
$P_{APS} = \text{filter model (approval) + organism* flow + RH + approval + (organism* flow) + (organism* RH) + (approval* organism) + (flow* RH* organism) + (approval* organism* RH)}$	ANOVA	$P_{APS}$	Filter model (approval) organism flow RH approval organism* flow organism* RH approval* organism flow* RH* organism approval* organism* RH	21 filters with 4 approvals, 2 flows, 2 RH	3 per condition
$P_{APS} = P_{PSL} + \text{flow + RH + organism + (organism*flow) + (organism* RH)}$	Regression	$P_{APS}$	$P_{PSL}$ flow RH organism organism* flow organism* RH	<u>bacterial</u> : 21 filters with 4 approvals, 2 flows, 2 RH <u>PSL aerosol</u> : 21 filters with 4 approvals, 1 flow, 1 RH	3 per condition 3 per condition

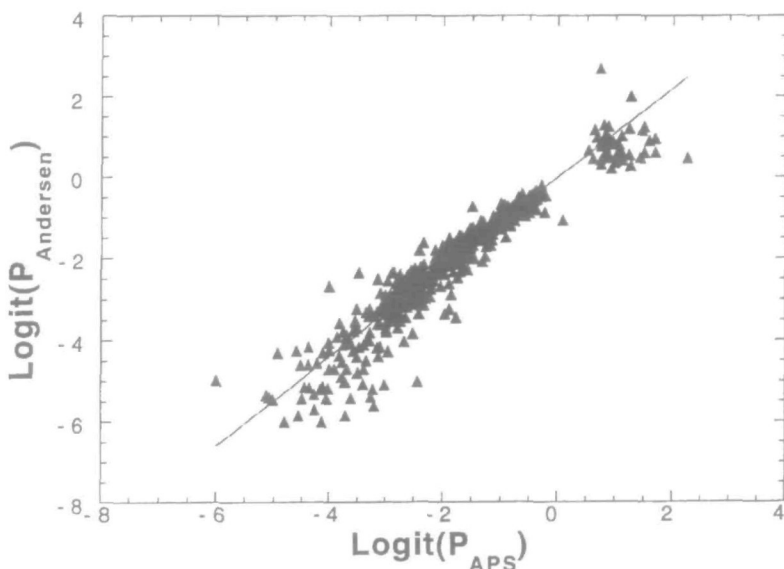


Fig. 1. Comparison of bioaerosol penetration measured using a viable particle sampler ( $P_{AND}$ ) and a direct-reading particle counter and sizer ( $P_{APS}$ ).

#### Filter performance tests employing bioaerosols

Because of the strong correlation between  $P_{APS}$  and  $P_{AND}$ , only those results obtained using the APS were analyzed. The factors of filter model (manufacturer), organism, flow, relative humidity, and approval category were all found to be statistically significant contributors to filter penetration as measured by the APS (Table 4). The results of multiple comparison tests (Table 4) of approval category were as expected with regards to penetration: NA > DM > DMF > HEPA (Fig. 2).

Table 4. Results of analysis of  $P_{APS}$  data

Variable	ANOVA results <i>p</i> value	Multiple comparison test results Statistical ranking of penetration
Filter Model (Approval)	< 0.0009	*
Organism	0.0001	<i>M.a.</i> = <i>S.e.</i> > <i>B.s.</i>
Flow	< 0.0009	85 l./min > 45 l./min
RH	0.006	30% > 70%
Approval	< 0.0009	NA > DM > DMF > HEPA
Flow × Organism	0.003	<i>B.s.</i> : 85 l./min > 45 l./min <i>S.e.</i> : 85 l./min = 45 l./min <i>M.a.</i> : 85 l./min > 45 l./min
RH × Organism	0.0001	<i>B.s.</i> : 30% = 70% <i>S.e.</i> : 30% = 70% <i>M.a.</i> : 30% > 70%
Approval × Organism	0.0015	NA: <i>M.a.</i> = <i>S.e.</i> = <i>B.s.</i> DM: <i>M.a.</i> = <i>S.e.</i> > <i>B.s.</i> DMF: <i>M.a.</i> = <i>S.e.</i> , <i>S.e.</i> = <i>B.s.</i> , <i>M.a.</i> > <i>B.s.</i> HEPA: <i>M.a.</i> = <i>S.e.</i> = <i>B.s.</i>
Approval × Organism × RH	0.02	*
Flow × RH × Organism	0.147	Not applicable

\*These multiple comparison tests were not conducted although the descriptive statistics were evaluated.

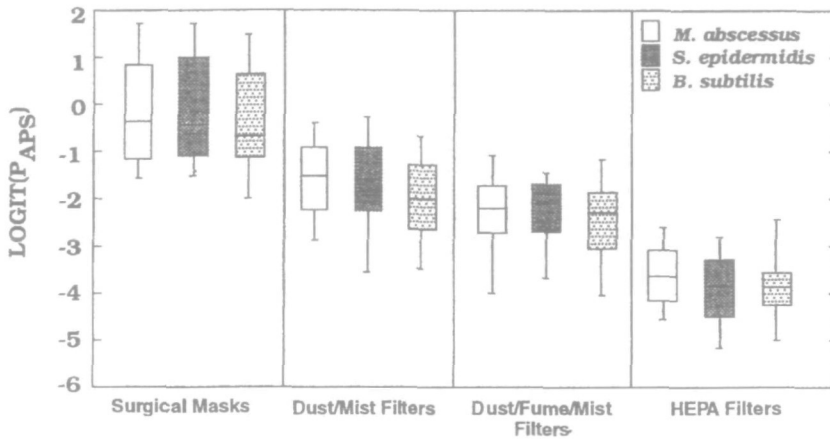


Fig. 2. Penetration (in the logit scale) measured with a direct-reading particle counter of three organisms for each of four filter approval categories.

Also as expected, higher flow resulted in significantly greater penetration. However, organism penetration did not respond similarly to changes in flow for all organisms. Testing *M.a.* and *B.s.* at higher flow resulted in significantly higher penetration than seen at low flow. For *S.e.*, however, differences between penetration at high (85 l./min) and low (45 l./min) flow rates were not statistically significant (Fig. 3).

The variables of organism and relative humidity did not behave as expected. If inertia and gravity are the primary collection mechanisms (which would be true for non-electrostatic respirator filters), particle aerodynamic diameter serves as a good

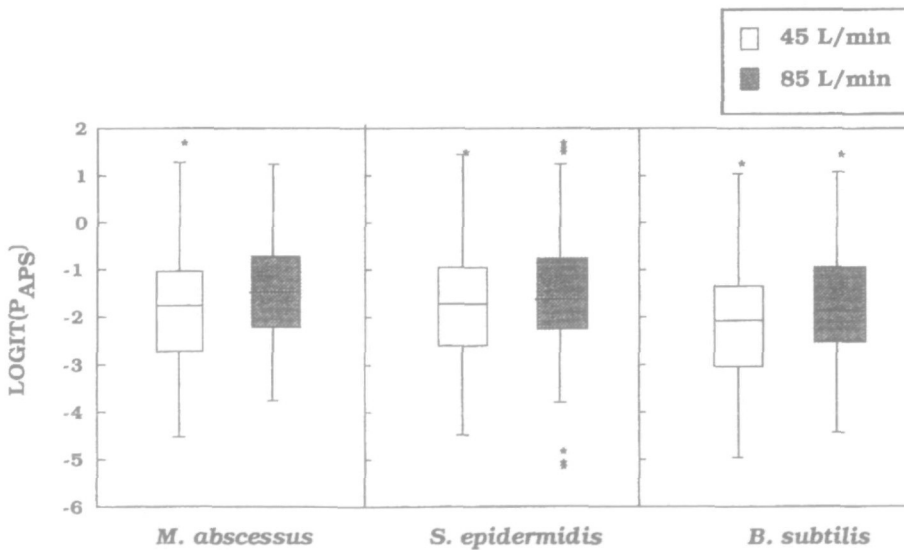


Fig. 3. Penetration (in the logit scale) measured with a direct-reading particle counter of three organisms at two conditions of flow.

surrogate for ranking penetration. Both predictions and measurements of aerodynamic diameter for the three organisms suggested a ranking for penetration with  $M.a. > S.e. = B.s.$  However, for all filters the multiple comparison test suggests a different ranking:  $M.a. = S.e. < B.s.$  (Table 4). When this was further examined by assessing the two-way interaction of approval category and organism, it was clear that the three organisms were collected somewhat differently in each of the approval categories (Fig. 2). For the NA and HEPA categories, all three organisms were collected with similar efficiency, while for the DM and DFM categories  $B.s.$  was more penetrating than either of the other two organisms.

While humidity was not originally expected to influence the penetration of these three organisms, the lower humidity condition resulted in higher penetration of all organisms when data for all filters were evaluated (Fig. 4). Further examination of the effect of relative humidity demonstrated, however, that this factor was significant only for  $M.a.$  (Table 4). Examination of the three-way interaction of approval category, relative humidity, and organism (not shown) indicated that  $M.a.$  was always more penetrating at the lower relative humidity condition, while the other two organisms were largely unaffected by relative humidity. Thus, within each approval category it is relative humidity which accounts for the differences in the collection of this organism when compared to the other two organisms. Relative humidity did not change the ranking of  $B.s.$  and  $S.e.$  within the four approval categories.

#### *Comparison of biological and non-biological aerosol penetration*

Filter penetration was evaluated using biological and non-biological aerosols and compared using linear regression analysis (Table 3). For each filter there were two sets of measurements: one using PSL spheres and one using bacterial aerosol. The PSL aerosol tests were conducted at one test condition; three replicates were evaluated for each filter model and the average penetration was used for comparison to the bacterial test data. The complete data set has been reported elsewhere (Brosseau *et al.*, 1997).

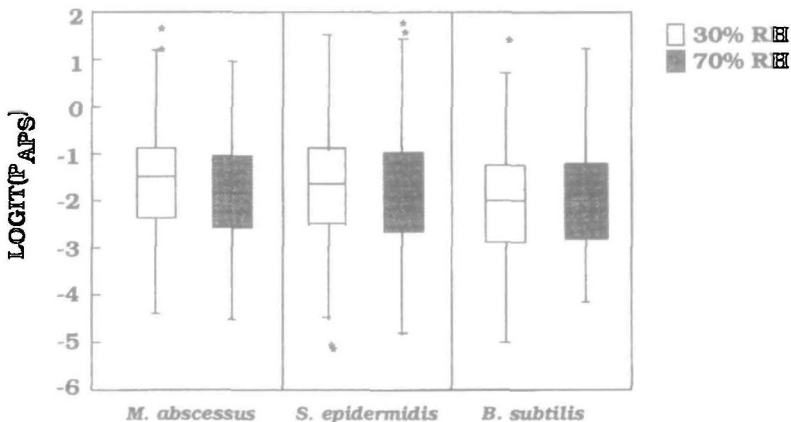


Fig. 4. Penetration (in the logit scale) measured with a direct-reading particle counter of three organisms at two humidity conditions.

Using the bacterial aerosol the penetration for each filter model was evaluated at 12 test conditions (3 organisms, 2 flows, 2 RH). For each filter the average of the PSL aerosol penetration (at the single test condition) was compared to each of the averages of penetration for the 12 test conditions using the bacterial aerosol. In every case, the penetration value was transformed using the logit transformation before comparison.

Linear regression analysis was then used to evaluate the relationship between the logit-transformed bacterial aerosol penetration data as measured by the APS and the logit-transformed PSL aerosol penetration data [Logit ( $P_{APS}$ ) and Logit ( $P_{PSL}$ ) respectively] for DM and DFM filters (Table 3). (Data from NA and HEPA filters were not included. Because they were found at the extremes of the scale, these points exerted considerable leverage in the linear regression analysis.)

The  $p$ -values of all factors are shown in Table 5. Two factors, organism and Logit ( $P_{PSL}$ ), were found to be statistically significant. Penetration of biological and non-biological particles was highly correlated, with an  $R^2$  value of 0.951.

Fitting the best line for each organism (Fig. 5) resulted in overlapping *M.a.* and *S.e.* lines; with the *B.s.* line below. This is similar to our findings from the ANOVA of the bioaerosol data alone, where penetration of *M.a.* and *S.e.* were more similar than that of *S.e.* and *B.s.* Penetration of the PSL aerosol is greater than that of any of the biological aerosols ( $P_{APS}$ ), which probably occurred because the PSL aerosol was smaller than any of the three biological aerosols.

#### DISCUSSION AND SUMMARY

It would appear that the aerodynamic diameter is not an accurate predictor for the penetration of these three aerosols. This is probably true for two reasons: (1) most of the tested filters do not rely entirely on mechanical forces (such as inertia and gravity) for collection of particles, and (2) relative humidity of the challenge air seems to play some role in the penetration of one of the organisms (*M.a.*).

While aerodynamic diameter is an appropriate representative for comparison among particles undergoing mechanical collection, it is probably not the best approximation when electrostatic forces are dominant. Previous work with asbestos aerosols and electrostatically-charged respirator filters showed that fiber length rather than aerodynamic diameter was a better predictor of penetration (Brosseau *et al.*, 1993). Another investigator has demonstrated that spherical particles are more

Table 5. Variables and  $p$ -values from linear regression analysis of  $P_{PSL}$  and  $P_{APS}$

Variable	$p$ -value
Organism	0.007*
Flow (of bioaerosol tests)	0.114
Relative Humidity (of bioaerosol tests)	0.085
PSL penetration (logit scale)	< 0.0009*
Organism*Flow	0.272
Organism*Relative Humidity	0.685

\*Significant at  $\alpha = 0.05$ .

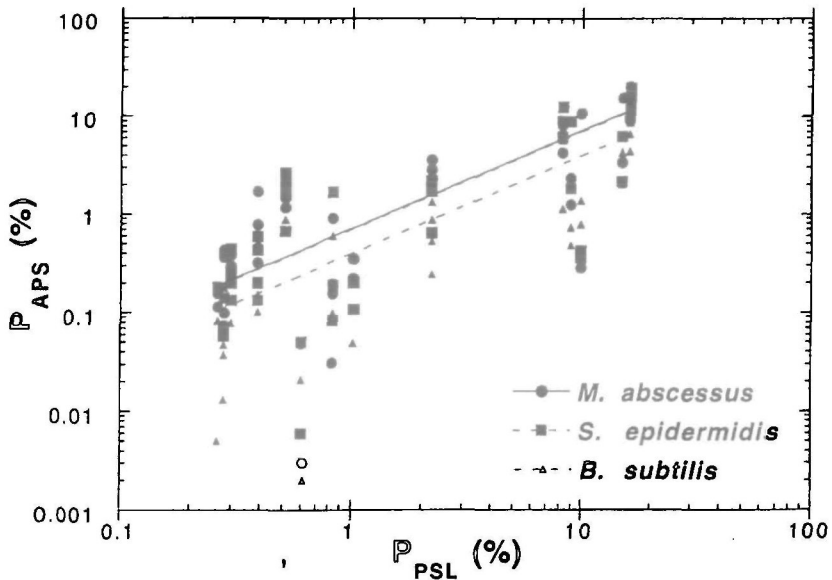


Fig. 5. DM and DFM filter penetration using three biological ( $P_{\text{APS}}$ ) and one non-biological aerosols ( $P_{\text{PSL}}$ ).

penetrating than non-spherical particles with similar aerodynamic diameters and that penetration decreased with increasing aspect ratio (Willeke *et al.*, 1996). In this case, neither aerodynamic diameter, aspect ratio nor length were accurate predictors of penetration among the three organisms.

There is no apparent explanation for the effect relative humidity was shown to exert on the penetration of *M.a.* The majority of organisms in this genus are hydrophobic (Wayne, 1994); perhaps this characteristic plays some role in its shape or charge state which alters the manner in which it is collected by these filters.

In conclusion, this research confirmed earlier findings that biological aerosol filtration behavior is greatly influenced by the physical properties of the particle (shape, size, density); we found no evidence that the biological properties (viability or chemical composition) influenced penetration. Results showed that test parameters, such as volumetric flow (and in turn face velocity), caused bioaerosol penetration to alter in a manner consistent with plausible physical collection mechanisms.

The correlation between the viable particle sampler and direct-reading particle detector demonstrates that viable sampling is not necessary for measuring filter penetration of biological aerosols. Although viable particle sampling may be necessary to initially characterize a particular test biological aerosol, future filter efficiency tests utilizing bioaerosols could be simplified by routine use of a non-viable sampler. In those cases where the microorganism of interest is hazardous (i.e. tuberculosis), a bioaerosol of similar size and shape could be substituted without concern for growth requirements and viability (Brosseau *et al.*, 1997).

Further, it may not be necessary to use a biological surrogate in order to predict filter penetration of bioaerosols. The correlation established between the filter

penetration of the two types of aerosols suggests that non-biological surrogates can be used in place of biological organisms, if the physical characteristics are similar. This is what would be expected based on known aerosol science.

These experimental results suggest that both electrostatic and mechanical forces were responsible for collection of the three organisms. A new parameter which describes filter collection of irregularly-shaped particles may be necessary. In addition, the role of relative humidity on mycobacterial aerosol penetration needs to be explored further.

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