American Industrial Hygiene Association Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/aiha20

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Yinge Qian [a], Klaus Willeke [a], Sergey A. Grinshpun [a] & Jean Donnelly [a]
[a] Aerosol Research and Exposure Assessment Laboratory, Department of Environmental Health, University of Cincinnati, Cincinnati, OH, 45267-0056 E-mail:
Published online: 18 Jun 2010.

To cite this article: Yinge Qian , Klaus Willeke , Sergey A. Grinshpun & Jean Donnelly (1997) Performance of N95 Respirators: Reaerosolization of Bacteria and Solid Particles, American Industrial Hygiene Association Journal, 58:12, 876-880, DOI: 10.1080/15428119791012216

To link to this article: http://dx.doi.org/10.1080/15428119791012216

Performance of N95 Respirators: Reaerosolization of Bacteria and Solid Particles

AUTHORS
Yinge Qian
Klaus Willeke*
Sergey A. Grinshpun
Jean Donnelly

Aerosol Research and Exposure Assessment Laboratory, Department of Environmental Health, University of Cincinnati, Cincinnati, OH 45267-0056; klaus.willeke@uc.edu

If a respirator does not contain an exhalation valve, and the respirator wearer sneezes or coughs, one may expect previously collected particles to be reaerosolized. This may be of special concern in environments contaminated with airborne microorganisms. The percentages of reaerosolization were measured in a test setup where the number of reaerosolized particles were registered by dynamic aerosol size spectrometry relative to the number of previously collected particles or bacteria. Experiments at low relative humidity have shown that the reaerosolization of particles below 1 μm, including *Mycobacterium tuberculosis* surrogate bacteria, does not exceed 0.025%, even if the re-entrainment air velocity is as high as 300 cm/sec (i.e., 37 times the air velocity through the respirator during breathing under heavy workload conditions). The reaerosolization of larger particles into dry air was significant at the highest re-entrainment velocity of 300 cm/sec, which simulates violent sneezing or coughing: 0.1% for 3 μm and about 6% for 5-μm test particles. No reaerosolization was detected at relative humidity levels exceeding 35% at these conditions. Thus, it is concluded that the reaerosolization of particles and bacteria, collected on the fibrous filters of N95 respirators, is insignificant at conditions encountered in respirator wear.

Keywords: efficiency, filter, microorganism, *Mycobacterium tuberculosis*, reaerosolization, respirator

In recent years, infections due to tuberculosis bacteria (TB) have increased and gained considerable attention because of the appearance of multidrug resistant *Mycobacterium tuberculosis*.[1] Since engineering controls cannot totally protect physicians, nurses, and other health care workers from TB patients, the Centers for Disease Control and Prevention in 1994 issued guidelines for respirator wear in health care facilities where there is risk of TB transmission.[2] In June of 1995 new regulations, drafted by the National Institute for Occupational Safety and Health, were issued for nonpowered particulate respirators (42 CFR 84).[3] The new regulations, which replace the previous ones at 30 CFR 11,[4] require that all certified particulate respirators have an efficiency of 95% or greater at the most penetrating particle size (ca. 0.1 to 0.3 μm) when tested at a flow rate of 85 L/min. All respirators that are certified under these new regulations are permitted to be worn for protection against TB.

The most prominent new respirator used in health care environments, satisfying the 95% minimum efficiency requirement, is the N95 respirator (which is tested with NaCl particles). Recent tests with airborne bacteria simulating the size and shape of TB bacteria have shown that the tested N95 respirators are over 99.5% efficient against bacteria of TB size.[5] Thus, N95 respirators offer good protection in TB environments if there is no face seal leakage between the respirator and the wearer's face.[6] The questions addressed by the present study are: can particles—in particular, bacteria of TB size and shape—be reaerosolized from these new respirators during exhalation and, if so, under what

*Author to whom correspondence should be addressed.
The authors appreciate the financial support of the National Institute for Occupational Safety and Health through grant R01-OH-03244. Yinge Qian was partially supported by a University of Cincinnati assistantship.

conditions? If bacteria are re-entrained by the exhalation flow, they may re-enter the surrounding air and be transmitted to another location; i.e., respirators with collected bacteria may become secondary contamination sources.

Very little information is available on the reaerosolization of particles from a filter. In a 1961 study the reaerosolization of silica dust with a mean particle size of 1.3 μm was recorded by the reduction in pressure drop across the filter as the particle load was reduced.[7] This method cannot be used to predict the reaerosolization of a small number of bacteria from a respirator filter. In another (1958) study, the dislodging of 10- to 800-μm particles from a single fiber was investigated by microscopic observation of the particles before and after an air jet was applied to the filter.[8] This method also is inadequate for accessing particle reaerosolization from a respirator filter, as the flow dynamics through a fibrous filter are more complex. In the present study dynamic aerosol size spectrometry was used to measure the reaerosolization of particles, including TB surrogate bacteria, under conditions that simulate respirator wear.

EXPERIMENTAL METHODS AND MATERIALS

When a respirator is worn, airborne biological particles such as bacteria, fungi, and pollen grains, and nonbiological particles such as dust, mist, and fume are collected by the filter of the respirator. Since some of these particles may penetrate through an N95 respirator, the aerosol concentration was measured up- and downstream of the respirator in the loading phase of this study (see Figure 1A). In this setup, biological or nonbiological particles were aerosolized from a Collison nebulizer (BGI Inc., Waltham, Mass.). To be compatible with the aerosol instruments, the aerosol was diluted to about 1.5×10^4 particles/cm^3 by mixing it with clean air. Before exposure to the test respirator the aerosol was charge-neutralized by passage through a 10 mCi ^{85}Kr electrostatic neutralizer (TSI, Inc., St. Paul, Minn.). All loading tests were performed at room conditions kept constant at a temperature of about 25°C and a relative humidity of about 22%. This test setup for loading the respirators is similar to the one used in previous aerosol penetration studies.[5,9]

The half-mask respirators used in this study were loaded for 30 to 50 minutes at a flow rate of 85 L/min, which corresponds to the breathing flow rate under heavy work load conditions.[4,10] This flow rate is required for certification under the new regulations[3] and results in a loading velocity through the filter of about 8 cm/sec. The aerosol concentrations up- and downstream of the respirator were measured by an aerosol size spectrometer (Aerosizer, Amherst Process Instruments, Inc., Hadley, Mass.). The Aerosizer is particularly useful for experiments with airborne bacteria because it can measure airborne bacteria down to about 0.5 μm,[11,12] below the 0.8-μm mean aerodynamic diameter of TB surrogate bacteria.[12–14] The total number of particles collected by the filter (i.e., the filter load, L) is calculated by measuring the volumetric airflow rate through the respirator during loading (Q_L), the loading time (t_L), the upstream aerosol concentration (C_{up}), and the downstream concentration (C_{down}). The ratio of the two aerosol concentration measurements yields the filter collection efficiency (E).

$$E = 1 - \frac{C_{down}}{C_{up}} \quad (1)$$

Thus,

$$L = Q_L E C_{up} t_L \quad (2)$$

The particle load was about the same for the NaCl and polystyrene latex (PSL) particles: 10^5 particles/cm^2. The particle size distribution decreased with particle size for both particle types.[15] The loading lasted about 30 minutes and did not increase the pressure drop across the filter. Thus, all reaerosolization experiments reflect initial particle loading where particles deposited on the filter's fibers do not interfere with each other. Exploratory experiments with filters overloaded with NaCl particles showed increased particle reaerosolization. However, reaerosolization as a function of mass loading was not pursued in this study. The bacterial loading also lasted about 30 minutes and reached approximately the same loading density of 10^5 bacteria/cm^2. Thus, all three types of particles used in these experiments were loaded so that there was only particle-to-fiber interaction, but no particle-to-particle interaction in the reaerosolization phase.

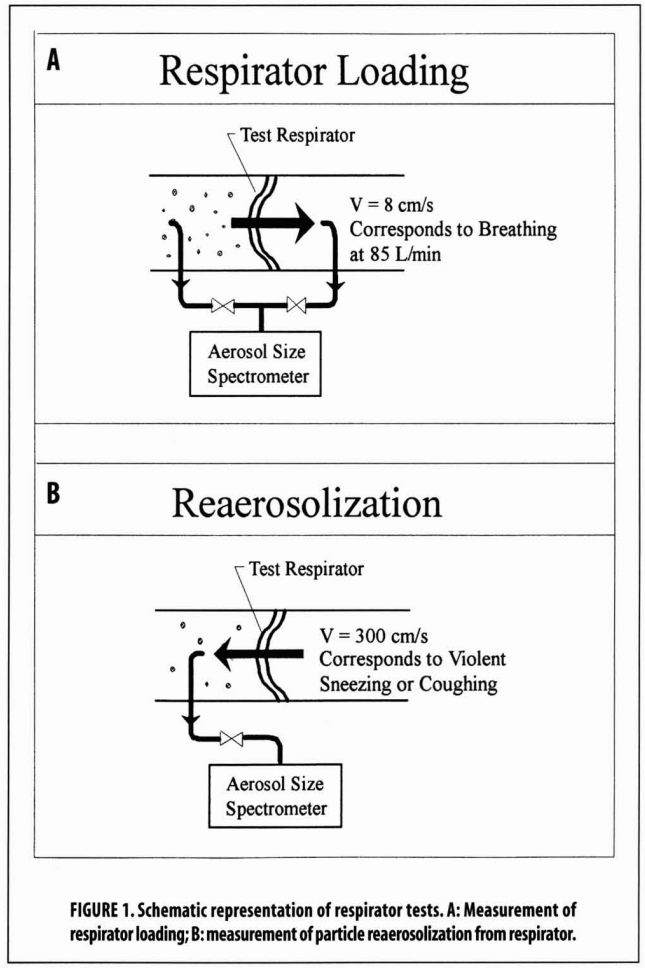

FIGURE 1. Schematic representation of respirator tests. A: Measurement of respirator loading; B: measurement of particle reaerosolization from respirator.

Figure 1B shows that the flow direction in the particle reaerosolization experiments is opposite to the loading direction, thus representing the exhalation cycle of respirator wear. The maximum reaerosolization velocity tested was 300 cm/sec, i.e., 37 times the loading velocity. This velocity simulates very adverse exhalation conditions, such as violent coughing or sneezing. This maximum velocity was determined by the following assumptions: 2 liters of lung tidal volume are exhaled during a 0.3-second period of violent coughing or sneezing through a mouth area of 22 cm^2.[16] The percentage of reaerosolized particles (R) as measured by the Aerosizer is

$$R = \frac{\text{No. of Reaerosolized Particles}}{\text{No. of Loaded Particles}} \times 100\% \qquad (3)$$

The nonbiological test particles selected for the experiments were (1) NaCl particles, which are used for certifying N95 respirators under the new regulations,[3] and (2) PSL particles, which are commonly used for testing and calibrating because of their spherical shape and their availability in many monodisperse particle sizes. In selecting the test bacteria, two requirements had to be met: (1) they must be nonpathogenic and (2) they must have a size and shape similar to *M. tuberculosis*.[17] Based on these requirements, *Bacillus subtilis* ATCC 6051 (American Type Culture Collection Inc., Rockville, Md.) was chosen as the TB surrogate because of its 0.7 to 0.8-μm width and 2 to 3-μm length.[18] To cover a broader spectrum of bacterial sizes, tests were also conducted with *B. megatherium* ATCC 14581, which is 1.2 to 1.5 μm wide and 2 to 5 μm long.[18]

The procedure for preparing the bacteria for the tests was the same as the one used in previous experiments.[9,12,19] Both bacterial cells were stored on a Tryptic soy agar slant at 5°C (Difco Laboratories, Detroit, Mich.). Before the aerosol experiments were started, the cells were streaked onto Tryptic soy agar plates and incubated at 25°C for 18 hours after incubation. They were moved off the plates with sterile deionized water and washed with deionized water in a centrifuge at 2860 × g (Marathon 6K, Fisher Scientific, Pittsburgh, Pa.). The washing removed residues from the liquid suspension so that the Aerosizer would count only bacteria.[12,19]

The NaCl particles were generated from a 3.5 mg/cm^3 solution of NaCl (Fisher Scientific, Pittsburgh, Pa.). The PSL particles were generated from water suspensions of monodisperse 0.60, 1.02, 2.94, 3.96, and 5.10-μm PSL particles (Bangs Laboratory, Carmel, Ind.).

Three models of N95 half-mask respirators, certified under the new 42 CFR 84 regulations, were chosen for the tests. Each of the three models represented a different manufacturer and contained charged polypropylene filters sandwiched between an inner and an outer cover web. In the data presentation these models are distinguished from each other by the labels A, B, and C. To measure the reaerosolization from an entire respirator as it is worn, no part of the test respirators was removed for the tests.

For each model, one was randomly selected from its supply box and was equilibrated at the test conditions for more than 24 hours prior to being tested. At least five tests were performed at each test condition. The presented data show the means and standard deviations for each test.

RESULTS AND DISCUSSIONS

Prior to performing reaerosolization experiments with bacteria, the three N95 respirator models were first performance-tested relative to the new regulations, i.e., with NaCl certification aerosols. Figure 2 shows the percentage penetration (P) of NaCl particles as a function of their aerodynamic diameter (d_a). The penetration is the ratio of C_{down} to C_{up}, as measured by the Aerosizer; i.e., P = 1−E. As seen, the maximum NaCl particle penetration, tested at the certification flow rate of 85 L/min, is less than 4% for N95 respirators of Companies A and B and slightly less than 5% for the respirators of Company C. Thus, all three respirators satisfy the certification requirement of 95% or more in collection efficiency.

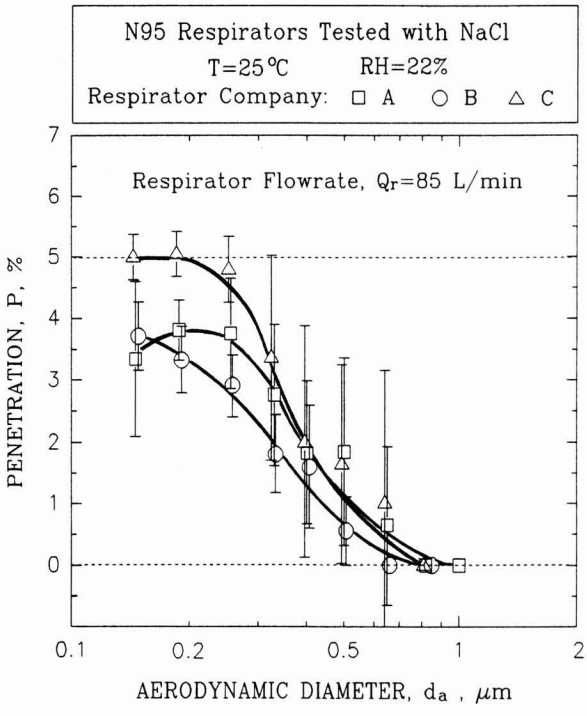

FIGURE 2. NaCl particle penetration through N95 respirators manufactured by three different companies, tested at the certification flow rate of 85 L/min

Reaerosolization of NaCl particles from these respirators is shown in Figure 3. Essentially no NaCl particles of d_a<1 μm were registered by the Aerosizer. The reaerosolization of 1-μm NaCl particles was about 0.007% for all three respirator models; i.e., less than 1 particle per 10,000 collected particles was re-entrained by an

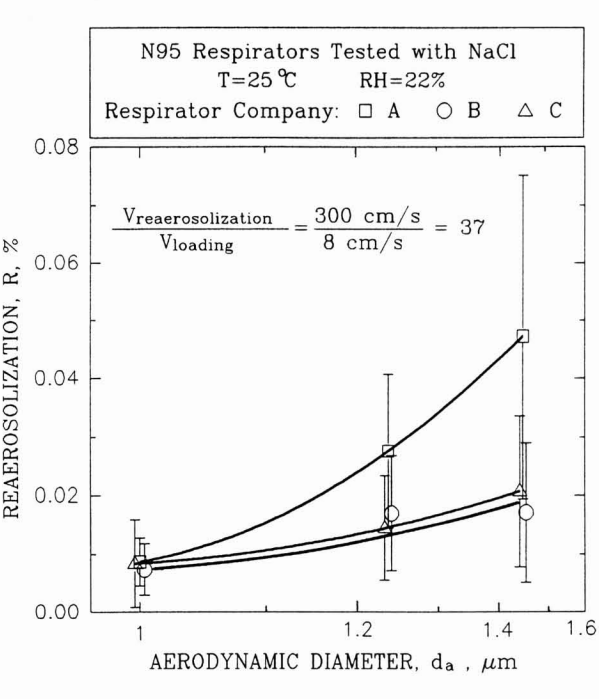

FIGURE 3. NaCl particle reaerosolization from N95 respirators manufactured by three different companies, tested at a reaerosolization velocity of 300 cm/sec

airflow representing the burst of airflow during violent sneezing or coughing. By varying the rise time between no flow and full reaerosolization flow from 300 msec to 10 sec, the percentage reaerosolization was found to be dependent only on the magnitude of the reaerosolization velocity. Oscilloscopic time records of the reaerosolized particles have shown that all particles are re-entrained within milliseconds of reaching the maximum re-entrainment velocity.[15] Reaerosolization was, therefore, only recorded over a period of 30 sec. As also seen in Figure 3, reaerosolization increased with particle size, reaching about 0.02 to 0.05% in mean reaerosolization at d_a = 1.4 μm. Too few NaCl particles were on the respirator filter above 1.4 μm to result in measurable reaerosolization, as the count mean diameter of the aerosolized NaCl solution was about 0.2 μm.

Figure 4 shows that the reaerosolization of NaCl and PSL particles and TB surrogate bacteria is a function of particle size. The insert shows that the reaerosolization percentage is less than 0.05% for particle sizes below 1.5 μm. In this figure the reaerosolization velocity simulates violent sneezing or coughing. Theoretically, one expects some difference between the reaerosolization percentages of different types of particles, because particle shape may influence the re-entrainment of particles as air flows over them. However, such differences are not discernable at this low level of reaerosolization. The reaerosolization of TB surrogate bacteria was found to be about 0.02%, irrespective of whether the bacteria were electrically charge neutralized by the ^{85}Kr radioactive source or were in their natural state as aerosolized by the Collison nebulizer. Thus, the degree of reaerosolization is insignificant for particles below 1.5 μm, irrespective of their composition and charge level.

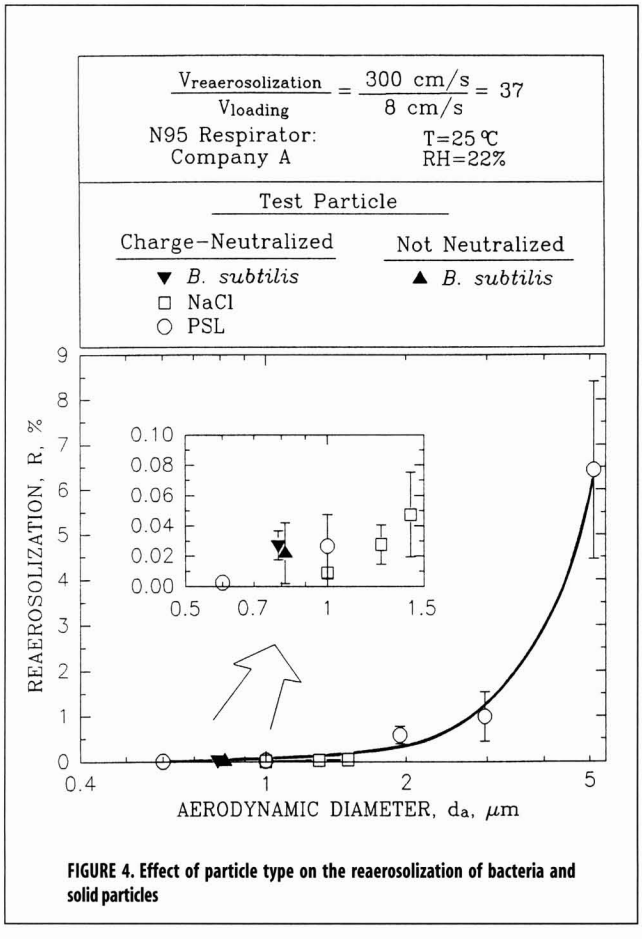

FIGURE 4. Effect of particle type on the reaerosolization of bacteria and solid particles

For large particles, however, reaerosolization may become significant. As seen in Figure 4, about 6 to 7% of 5-μm PSL particles were reaerosolized. These data are shown because single bacteria (on the order of d_a = 1 μm) may aggregate and form a larger bacterial cluster, or they may be attached to larger inert particles. The authors attribute the nonlinear increase in reaerosolization with particle size to the particle size dependence of the adhesion and aerodynamic drag forces. The particle adhesion forces increase with particle size in an essentially linear relationship, while the aerodynamic drag force increases with the square of particle size.[20,21]

Figure 5 shows the effect of reaerosolization velocity on the reaerosolization of NaCl particles and two types of bacteria, *B. subtilis* and *B. megatherium*. For each bacterium the data are shown for a typical size. These sizes are close to those of *M. tuberculosis*. No reaerosolization was registered by the Aerosizer below reaerosolization velocities of 200 cm/sec, which is about 25 times the loading velocity. As the reaerosolization velocity increases to twice that value, 400 cm/sec, reaerosolization increases nonlinearly but remains at an insignificant level. The curves are best fits connecting the data. Since these data are close to the threshold of detection of the test setup, they cannot be interpreted as to their dependence on air velocity. At the 400 cm/sec reentrainment velocity, the bacteria appear to be re-entrained more easily than the NaCl particles, which may indicate a weaker bond to the filter fibers or more surface area sticking into the airflow, thus facilitating aerodynamic re-entrainment.

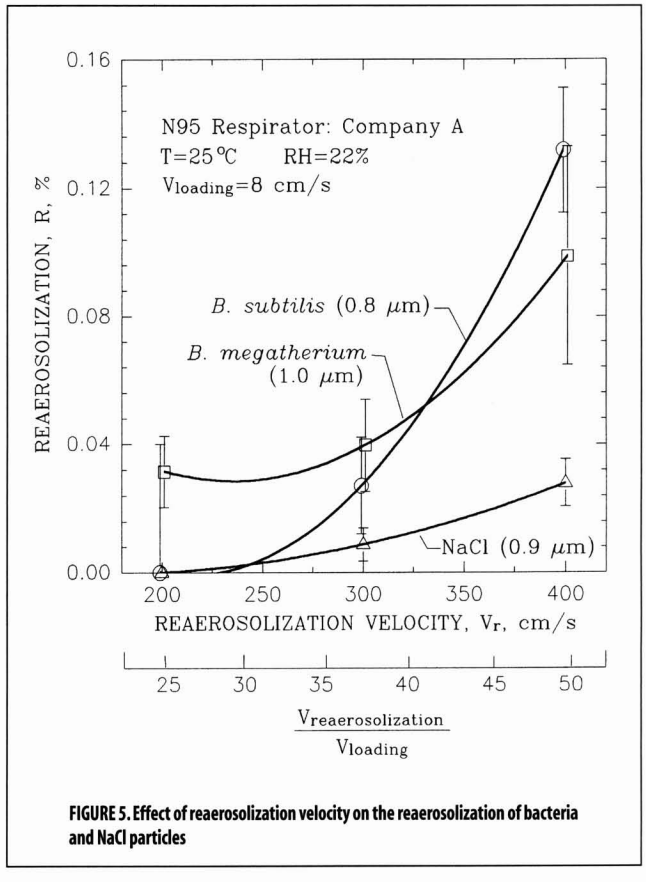

FIGURE 5. Effect of reaerosolization velocity on the reaerosolization of bacteria and NaCl particles

Experiments with filter materials of the same manufacturer, but of different thickness, have not shown any increase or decrease in reaerosolization with filter thickness, i.e., the majority of reaerosolized particles and bacteria is collected on and dislodged

from the top layer of the respirator filter. All of the above measurements were made at a relative humidity of 22%. When the relative humidity was increased to levels of 35% or higher, no reaerosolized particles were detected by the Aerosizer. This decrease in reaerosolization with increasing relative humidity is attributed to liquid bridging between particles and filter fibers that increases the adhesion force. Since the exhaled airflow of a worker wearing a half-mask respirator is saturated with water vapor, the respirator filter may be at a higher humidity level than the external air. Thus, the data show the maximum reaerosolization that may occur.

CONCLUSIONS

This study has shown that inert particles and TB surrogate bacteria of d_a = 0.8 μm, collected on N95 respirators, are not reaerosolized during normal respirator wear. When the respirator wearer coughs or sneezes at exhalation air velocity exceeding 25 times the breathing velocity through the respirator under heavy work load conditions, some of the particles and bacteria may reaerosolize. At air velocities of 300 cm/sec, corresponding to 37 times the inhalation air velocity through the respirator filter, the reaerosolization of TB surrogate bacteria as well as NaCl and PSL particles below 1 μm is 0.025% or less, when the respirator and airflow are at a relative humidity level of 22%. At this condition of violent sneezing or coughing, only larger particles are reaerosolized in significant amounts: 1% of 3-μm and about 6% of 5-μm PSL particles. No reaerosolization was detected at relative humidities exceeding 35%. Thus, reaerosolization of TB bacteria and other particles less than a few micrometers in size, collected by the respirator filter during inhalation, is insignificant at conditions encountered in respirator wear.

Since most respirators with 99% or higher efficiency at the most penetrating particle size contain the same or similar filter material as the 95% efficient respirator, but have a thicker layer of it, the above conclusions are likely to be valid for all fibrous filter materials used in respirators. If bacteria reproduce themselves during respirator storage under favorable conditions, the new bacteria may not be attached to the filter fibers, but to other bacteria. Further research will examine whether bacteria can reproduce on respirators and whether the new bacteria can be reaerosolized from the filter.

REFERENCES

1. **Broom, B.R. and C.J. Murray:** Tuberculosis: commentary on a reemergent killer. *Science 257*:1055–1064 (1992).

2. **Centers for Disease Control:** Guideline for preventing the transmission of mycobacterium tuberculosis in health-care facilities. *Morb. Mort. Wkly. Rep. 43*: RR-13 (1994).

3. "42 CFR Part 84 Respiratory Protection Devices; Final Rules and Notice," *Federal Register 60*:110 (8 June 1995). pp. 303336–30404.

4. "Mineral Resources," *Code of Federal Regulations* Title 30, Part 11. 1994. pp. 46–108.

5. **Qian, Y., K. Willeke, S.A. Grinshpun, J. Donnelly, et al.:** Performance of N95 respirators: filtration efficiency for airborne bacteria and solid particles. *Am. Ind. Hyg. Assoc. J.* [In press].

6. **Han, D.H., K. Willeke, and C.E. Colton:** Quantitative fit testing techniques and regulations for tight-fitting respirators: current methods measuring aerosol or air leakage, and new developments. *Am. Ind. Hyg. Assoc. J. 58*: 219–228 (1997).

7. **Corn, M. and L. Silverman:** Removal of solid particles from a solid surface by a turbulent air stream. *Am. Ind. Hyg. Assoc. J. 22*:337–347 (1961).

8. **Larsen, R.I.:** The adhesion and removal of particles attached to air filter surfaces. *Am. Ind. Hyg. Assoc. J. 19*:265–270 (1958).

9. **Willeke, K., Y. Qian, J. Donnelly, S.Grinshpun, et al.:** Penetration of airborne microorganisms through a surgical mask and a dust/mist respirator. *Am. Ind. Hyg. Assoc. J. 57*:348–355 (1996).

10. **Johnson, A.T., R.A. Weiss, and C. Grove:** Respirator performance rating table for mask design. *Am. Ind. Hyg. Assoc. J. 53*:193–202 (1992).

11. **Cheng, Y.S., E.B. Barr, I.A. Marshall, and J.P. Mitchell:** Calibration and performance of an API aerosizer. *J. Aerosol Sci. 24*:501–514 (1993).

12. **Qian, Y., K. Willeke, V. Ulevicius, S.A. Grinshpun, et al.:** Dynamic size spectrometry of airborne microorganisms: laboratory evaluation and calibration. *Atmos. Environ. 29*:1123–1129 (1995).

13. **Chen, S.-K., D. Vesley, L.M. Brosseau, and J.H. Vincent:** Evaluation of single-use masks and respirators for protection of health care workers against mycobacterial aerosols. *Am. J. Infect. Control 22*:65–74 (1994).

14. **Jonson, B., D.D. Martin, and I.G. Resnick:** Efficacy of selected respiratory equipment challenged with *Bacillus subtilis* subsp. *niger. Appl. Environ. Microbiol. 60*:2184–2186 (1994).

15. **Qian, Y., K. Willeke, V. Ulevicius, and S.A. Grinshpun:** Particle reentrainment from fibrous filters. *Aerosol Sci. Technol. 27*:394–404 (1997).

16. **The International Commission on Radiological Protection:** *Human Respiratory Tract Model for Radiological Protection.* Oxford, UK: Pergamon, 1993. pp. 22–25.

17. **Wayne, L.G. and G.P. Kubica:** Mycobacteria. In *Bergey's Manual of Systematic Bacteriology,* vol. 2, P.H.A. Sneath, N.S. Mair, M.E. Sharpe, and J.G. Holt, eds. Baltimore, MD: Williams & Wilkins Co., 1984. pp. 1436–1447.

18. **Claus, D. and C.W. Berkeley:** Bacillus. In *Bergey's Manual of Systematic Bacteriology,* vol. 2, P.H.A. Sneath, N.S. Mair, M.E. Sharpe, and J.G. Holt, eds. Baltimore, MD: Williams & Wilkins Co., 1984. pp. 1105–1139.

19. **Terzieva, T., J. Donnelly, V. Ulevicius, S.A. Grinshpun, et al.:** Comparison of methods for detection and enumeration of airborne microorganisms collected by liquid impingement. *Appl. Environ. Microbiol. 62*: 2264–2272 (1996).

20. **Corn, M.:** Adhesion of particles. In *Aerosol Science,* C.N. Davis, ed. London: Academic, 1966. pp. 359–392.

21. **Zimon, D.A.:** *Adhesion of Dust and Powder.* New York: Consultant Bureau, 1982. pp. 136–348.