

Experimental and Theoretical Investigation of the Performance of N95 Respirator Filters against Ultrafine Aerosol Particles Tested at Constant and Cyclic Flows

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ABSTRACT

Filtration efficiency of filtering facepiece particulate respirators (FFPR) against ultrafine aerosol particles is drawing increasing attention. The filter performance is conventionally tested at a constant flow, and the data generated in this testing are used to predict filtration efficiency when the respirator is donned on a breathing subject. The objective of this study was to determine the experimental and theoretical differences in performance of NIOSH certified N95 FFPRs against ultrafine aerosols when the respirators are tested at constant versus cyclic flow conditions. Two commercially available N95 respirators sealed on a manikin were challenged with three fractions of ultrafine polystyrene latex (PSL) particles (25, 65 and 99 nm) at four flow rates (15, 30, 85, and 135 L min⁻¹) under constant and cyclic flow conditions. Penetration (P_{const} and P_{cyclic}) of monodisperse particles was determined as a ratio of aerosol concentrations measured inside and outside of the respirator. It was observed that penetration of ultrafine particles obtained under constant flow may be lower or higher than that obtained under cyclic flow. The difference in performance tested in the two regimes is flow rate and particle size dependent. Statistically significant differences in the respirator filter penetration were found at 15 and 30 L min⁻¹ with P_{cyclic} exceeding P_{const} while essentially no difference was observed at 85 L min⁻¹ (the NIOSH certification flow rate) and a slightly reverse tendency was identified at 135 L min⁻¹. The findings are explained by applying filtration theory for estimating the particle collection on the FFPR fibers utilizing different mechanisms such as diffusion, electrostatic interaction, impaction, and interception.

Keywords: Filtration, Facepiece Respirator, Breathing Simulator, Ultrafine Aerosol

INTRODUCTION

Filtering facepiece particulate respirators (FFPRs) marketed in the United States for use in work place are subjected to performance certification conducted by NIOSH in accordance with 42 CFR 84.181 (Federal Register, 1995), which ensures that respirator filters meet a minimum requirement under controlled laboratory conditions. The filtration test is designed to be conservative by preconditioning the filters and challenging them with a charge-neutralized aerosol with a mass median aerodynamic diameter (MMAD) of ~300 nm, which is assumed to be the most penetrating particle size. The test is performed at a constant flow rate of $Q = 85 \text{ L min}^{-1}$. The particle penetration through the tested filter is determined by measuring the challenge aerosol concentrations upstream and downstream of the filter. This test is designed to evaluate filter penetration and does not address face seal leakage.

The data obtained under steady-flow conditions are conventionally used to predict the minimum respirator filtration efficiency when it is donned on a breathing subject. When inhaling, the velocity of aerosol flow passing through a filter increases from zero to some maximum value and then decreases back to zero, followed by similar reversal in flows when exhaling. Although this non-steady, cyclic flow depends on numerous factors (representing the complexity of the human breathing pattern), the air velocity can be approximated by a sinusoidal function of time.

The differences in the respirator filter performance obtained under constant and cyclic flow have been studied by several investigators. Jordan and Silverman (1961) tested a fiberglass filter with particles of $0.78 \mu\text{m}$ count median diameter (CMD) and a geometric standard deviation (σ_g) of 1.13, found that the penetration obtained with constant flow may under- or over-estimate that obtained with cyclic-flow, depending on the time-averaged mean air velocity. Stafford et al. (1973) measured the penetrations of seven monodisperse polystyrene latex (PSL) fractions ranging from 0.176 to $2.02 \mu\text{m}$ and one dioctyl phthalate (DOP) aerosol fraction of $0.3 \mu\text{m}$ through respirator filter cartridges at three cyclic breathing flows with mean inspiratory flow (MIF) rates of 30, 35, and 53 L min^{-1} . MIF is defined as the flow rate integrated over the inhalation portion of the breathing cycle, or inspiratory duration. Tests were also conducted at a constant flow rate of 16 L min^{-1} per filter cartridge [equivalent to 32 L min^{-1} for a dual cartridge respirator, which was the US Bureau of Mines testing standard at the time (Federal Register, 1971)]. The investigators found that the maximum penetration was consistently higher under cyclic as compared to the constant flow conditions. They also reported differences in the most penetrating particle sizes (MPPS). Generally higher particle penetration under cyclic flow conditions was also reported by Brosseau et al. (1990) who compared the filter efficiency of air purifying dust/mist respirators challenged with silica particles (CMD = $0.46 \mu\text{m}$, $\sigma_g=2.5$) and asbestos fibers (median length = $4.5 \mu\text{m}$ at $\sigma_g=2.7$ and median width = $0.2 \mu\text{m}$ at $\sigma_g=2.5$) at 32 L min^{-1} . The comparison result depended on tested respirators.

While the above investigations have generated important information, they did not address the filter penetration of ultrafine particles ($\leq 0.1 \mu\text{m}$). In addition, the protection provided by respirators (especially NIOSH-certified FFPR) in this particle size range has gained increased attention because of

- (i) Considerable evidence suggesting that ultrafine fraction is particularly health-relevant and
- (ii) several recently published reports (Balazy et al., 2006a; Rengasamy et al., 2007; Eninger et al., 2008), which suggested that the peak penetration through N95 and N99 filters (made of electret media) occurs at particle sizes of tens of nanometers, contrary to the conventional mechanical filtration theory that established MPPS~300 nm.

To our knowledge, the only experimental work that compared the respirator filter penetration of ultrafine particles under constant and cyclic flow conditions was a report by Richardson et al. (2006), which featured the performance data of N95 and P100 NIOSH-certified respirators. Their testing targeted high work load conditions represented by mean inspiratory flows of 85 L min^{-1} and greater. The relative difference between the data generated in the cyclic- and constant-flow tests was found to be dependent on the particle size and varied among the tested respirators. While testing at 85 L min^{-1} is particularly important as this flow rate is utilized by the NIOSH certification program, real breathing rates are likely to be considerably lower in most of workplace environments, including (but not limited to) health-care and laboratory facilities as well as many industrial and agricultural settings.

The objective of this study was to expand the body of knowledge regarding filter efficiency of N95 FFPRs against ultrafine aerosols when tested at constant versus sinusoidal cyclic flow conditions.

MATERIALS AND METHODS

Test System

The experiments were performed using the experimental set-up shown in Figure 1. The respirator tested was sealed to a manikin face, checked for faceseal leaks with a bubble leak detector, and placed inside of a 0.096 m³ test chamber. Respirators were challenged with one of three different size fractions of monodisperse ultrafine PSL particles representing 25, 65 and 99 nm in physical diameter (d_{phys} , $\sigma_g < 1.1$) (Bangs Laboratories Inc., Fishers, IN). Each PSL fraction was diluted in ultrapure water and aerosolized with a 6-jet Collison nebulizer (BGI Inc., Waltham, MA). Freshly generated aerosol was diluted and dried with a HEPA-filtered air, charge-equilibrated to a Boltzmann charge distribution using a Kr⁸⁵ sealed source (model 3054, TSI Inc., Minneapolis, MN), and fed to the test chamber. The monodisperse aerosol concentrations inside and outside of the respirator were measured using condensation particle counters (P-Trak, TSI, Inc., St. Paul, MN), and the penetration was determined as a ratio of the two.

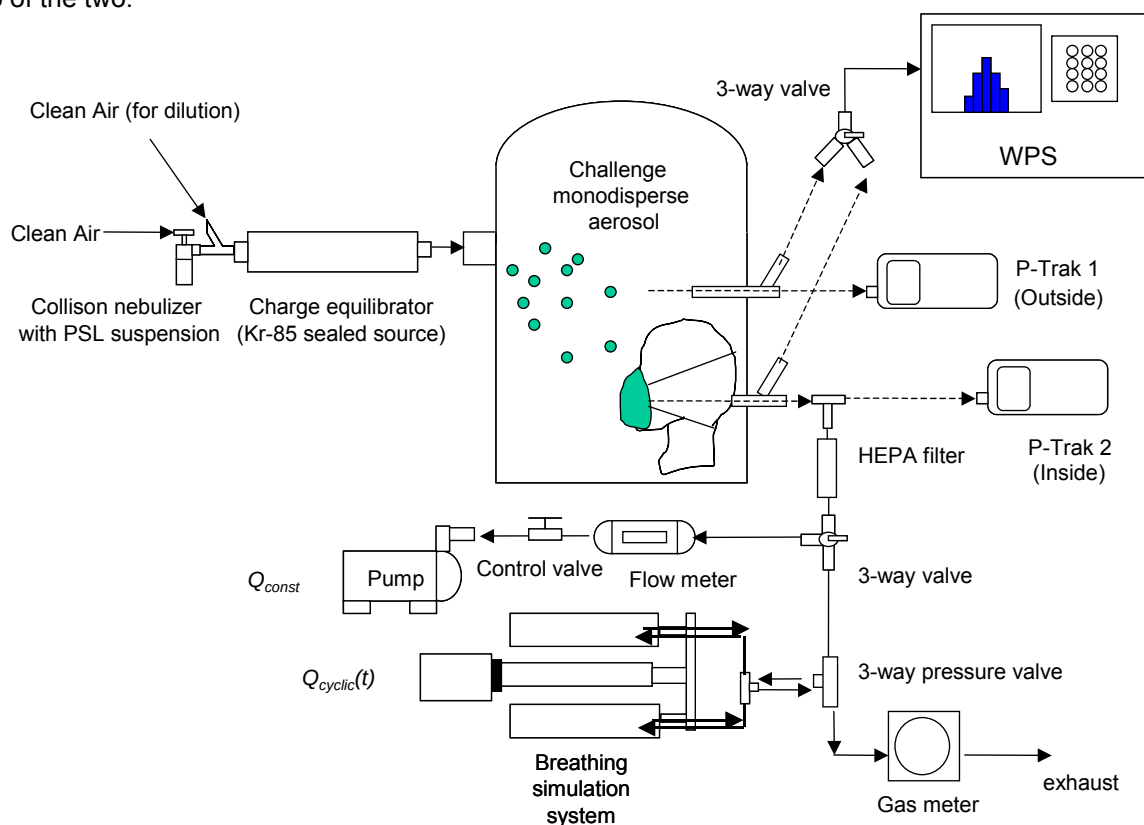


Figure 1. Experiment setup.

Prior to each test, the challenge aerosol was characterized in the test chamber using a size-selective Wide-range Particle Spectrometer (WPS, model 1000 XP, MSP Corp., Shoreview, MN) connected to a data acquisition system. While this instrument combines the differential mobility analysis (DMA), condensation particle count, and the laser particle spectrometry it was only necessary to use the DMA module (10 – 500 nm) for the challenge aerosols chosen for this study. Therefore, the size of particles was quantified and recorded based on their electrical mobility (Flagan, 2001). As a part of the experimental method validation, the WPS-measured aerosol size distributions were compared for inside and outside sampling lines with no respirator donned (ideally, these should be identical). The concentration differences were small suggesting that the sampling efficiencies of these lines were essentially the same.

Respirators

Two models of FFPRs commercially available from different manufacturers (referred to as A and B throughout the paper) were utilized in this study. Although both respirators have the same NIOSH classification of N95, respirator “A” has higher filter efficiency. The same models were also tested in an earlier study (Balazy et al., 2006a). Both are widely used in occupational environments and utilize charged polypropylene fibers (electret media) to enhance filtration efficiency. The tested respirators did not have exhalation valves.

Constant and Cyclic Flow Regimes

The constant inhalation air flow was supplied by a vacuum pump (model G272X, Doerr Electric Corp., Cedarburg, WI). The tests were performed at $Q_{\text{const}} = 15, 30, 85, \text{ and } 135 \text{ L min}^{-1}$. The first two flow rates represent light and moderate work loads. The third (85 L min^{-1}) has been used in many respirator performance studies and in the NIOSH respirator certification protocol; it is intended to represent a high work load. The fourth flow (135 L min^{-1}) represents a very high work load and approximately matches the Q_{PIF} reached by a cyclic flow with $Q_{\text{MIF}} = 85 \text{ L min}^{-1}$. The constant flow was measured with a flow meter (model 4045, TSI, Inc.). The cyclic flow was created by a special breathing simulation system developed and built by Koken Ltd. (Tokyo, Japan). The breathing simulation system consists of an electromechanical drive-cylinder and two air cylinders connected to each other. A sinusoidal air flow is generated as the electromechanical cylinder moves back (inspiratory duration, half a period) and forth (expiratory duration, half a period) thus driving the air cylinders, so the air flow rate applied to the tested respirator is changed accordingly. The torque of the electromechanical cylinder is as high as $3.92 \text{ kN}\cdot\text{m}$, which allows for high precision when using the breathing simulator with a respirator at high pressure drop. With a stroke of up to 25 cm , maximum frequency 0.5 Hz , and a total capacity of 6.0 L , the breathing simulator can generate a Q_{MIF} up to 360 L min^{-1} and Q_{PIF} of up to 600 L min^{-1} , which is at or in excess of the upper limit of human breathing (Richardson et al., 2006). The stroke distance can be adjusted with a resolution of 0.1 mm , thus allowing for very small flow rate changes when human breathing is simulated.

While this breathing simulator is capable of generating various inhalation and exhalation patterns, this study utilized a sinusoidal waveform as a reasonable approximation for testing performance of respirators (Stafford et al., 1973). Figure 2 illustrates the volumes and flows of a sinusoidal breathing pattern with a breathing rate of 10 times per minute at an inspiratory volume of 1.5 L (tidal volume = 3.0 L). The equation for this waveform is:

$$Q = Q_{\text{PIF}} \times \sin(2\pi t/T) \quad (1)$$

where, Q_{PIF} is the peak inspiratory flow, T is the breathing cycle time (period), and t is time.

Each of the four constant flows used in this study were compared to an equivalent cyclic flow having the same MIF rate, as described by the following equation:

$$\int_0^{T/2} Q(t) dt = Q_{\text{MIF}} = Q_{\text{const}} \quad (2)$$

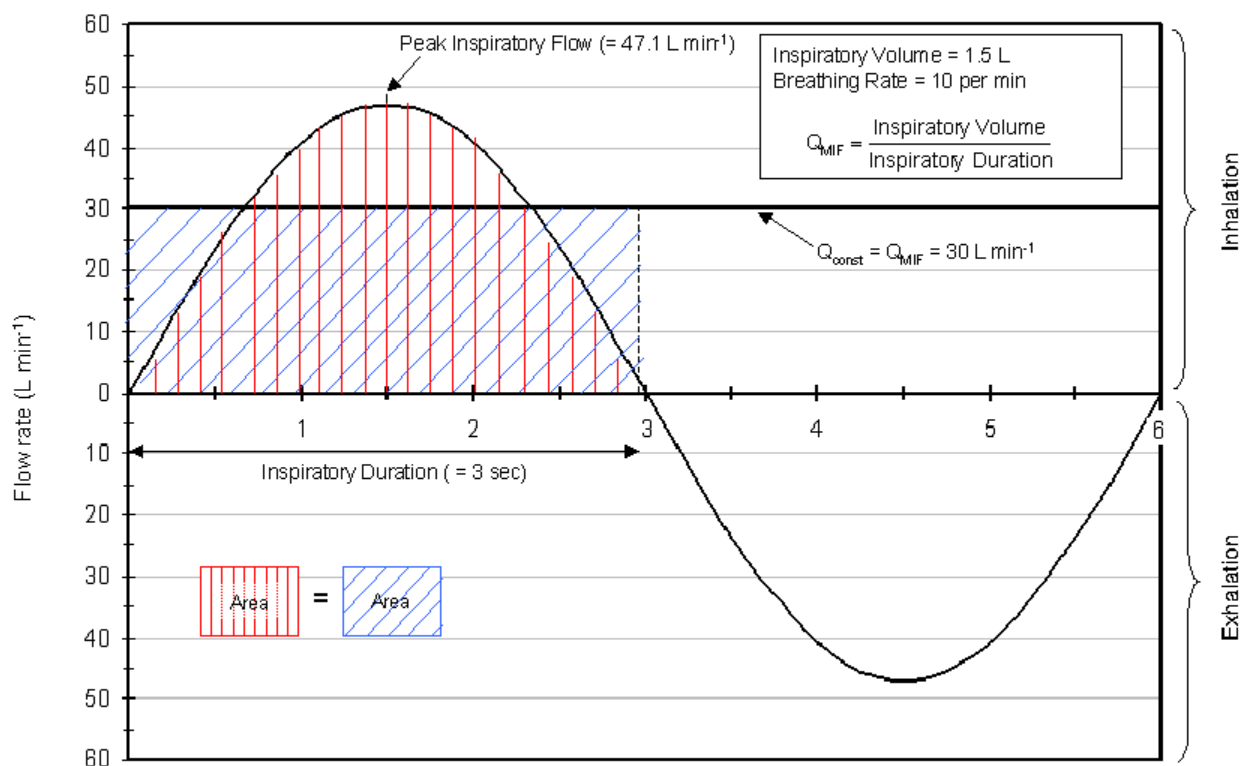


Figure 2. Volume and flows for representative sinusoidal breathing pattern.

For example, a constant flow of 30 L min^{-1} would have an identical Q_{MIF} (which is the ratio of the tidal inspiratory volume to the inspiratory duration) for cyclic flow when the inspiratory duration equals 3 seconds and inspiratory volume equals 1.5 L. The MIF has become the accepted convention for use as a cyclic-flow regime comparator and analog for constant flow (Richardson et al., 2006; Stafford et al., 1973). The peak inspiratory flow (Q_{PIF}) for this condition would equal 47.1 L min^{-1} .

The 3-way valve placed in front of the breathing simulator used pressure valves to prevent the challenge aerosol from returning to the sample lines during exhalation. A gas meter (model DC-5, Sinagawa Corp., Tokyo, Japan) was set at the end of the line to measure the exhalation air volume and subsequently determine the flow rate.

Data Analysis

At least three identical FFPRs of each of the two tested models were evaluated for each combination of flow rate and particle size. The mean value of penetrations and the standard deviation were calculated for each set of conditions. The penetration values obtained under the constant- and cyclic-flow conditions were compared through the paired t-tests utilizing Microsoft Office Excel (Microsoft Corp., Redmond, WA).

RESULTS

Particle Size Distribution of Challenge Aerosols

The particle size distributions of the three ultrafine PSL fractions used as challenge aerosols are shown in Fig. 3. Each curve represents a time-integrated data set as measured with the WPS in the chamber over a 3.5-min period (the instrument sampled through the “outside” line.) The concentrations measured without a respirator (inside line) were essentially identical to the outside sample line within 10% accuracy at all constant flows. The geometric standard deviations of the particle size distributions shown in this Figure are higher than the nominal σ_g of the respective PSL fractions. This is, however, an expected finding when nebulizing from a liquid suspension. The WPS-identified peak sizes are slightly greater than the corresponding physical diameters of PSL particles. This can be attributed to the difference between electrical mobility and physical sizes of particles. The relative difference was highest at 25 nm. Overall, although not perfectly monodisperse, the characteristics of the aerosol fractions were appropriate for use as challenge aerosols when determining the respirator filter performance based on the total counts provided by the P-Trak.

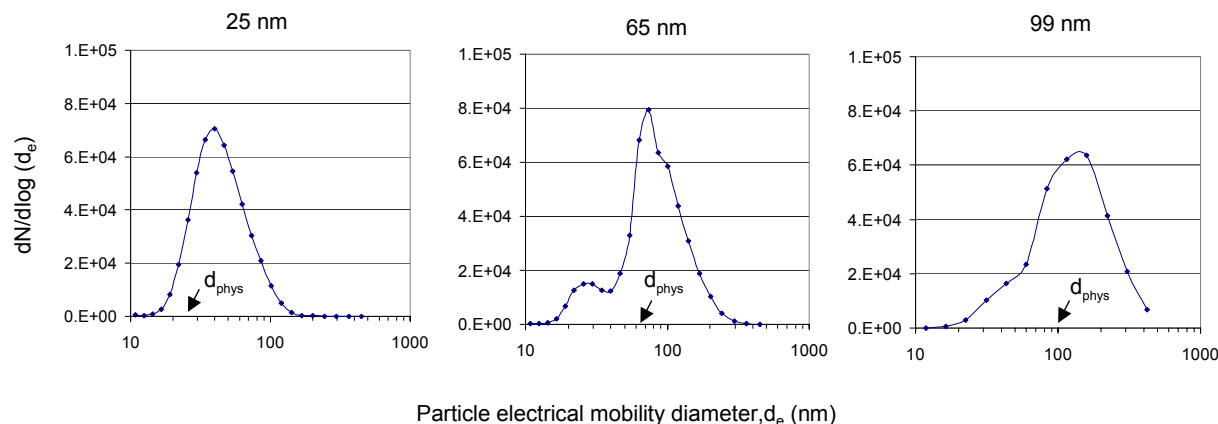


Figure 3. Size distributions of the three tested fractions of PSL particles measured with WPS.

Particle Penetration (Experimental Data)

The penetration data for the PSL particles under the constant- and cyclic flow conditions at different flow rates are summarized in Figure 4A for Respirator A and Figure 4B for Respirator B. As expected, the data demonstrate that penetration increases with increasing flow rate. This was observed for both types of flow patterns (constant and cyclic flow) for all three particle sizes. The above trend was anticipated because ultrafine particles are collected on N95 filters primarily by diffusion and electrical polarization mechanisms given that both tested filters consisted of materials (Balazy et al., 2006a). The higher flow through the filter means higher air velocity and a corresponding lower residence time, which reduces particle deposition on the filter fibers. The MPPS values are consistent with the results of Balazy et al. (2006a) who studied the same FFPR at constant flow (85 L min^{-1}). At flow rates of 15 L min^{-1} to 85 L min^{-1} , the average particle penetration through Respirators A and B did not exceed 5% with either flow regime. Respirator A is seen to be more efficient than B. Although Respirator B challenged with 65-nm particles at 85 L min^{-1} had <5% penetration (the value averaged from three replicates), one out of the three replicates exceeded 5% in both flow regimes. At a flow rate of 135 L min^{-1} , all of the measured penetration values exceed 5% (which was not surprising).

It is seen from Fig. 4 (A and B) that, when the inspiratory flow rates were relatively low (15 and 30 L min⁻¹), the cyclic-flow regime produced higher penetration values than the corresponding constant-flow regime. These differences were statistically significant ($p < 0.05$, t-test) or close to the significance level for all three particle sizes. In contrast, no statistically significant differences were found at 85 L min⁻¹. Moreover, at 135 L min⁻¹, a reverse tendency was observed so that the penetrations of all the tested ultrafine particles through both FFPRs were higher under the constant-flow conditions as compared to the cyclic flow. The data suggests that respirator filter testing with constant-flow regimes may not always be a good predictor of performance with cyclic-flow. For ultrafine particles, the constant flow penetration estimates may be higher or lower than those obtained with the cyclic flow, depending on the flow rate.

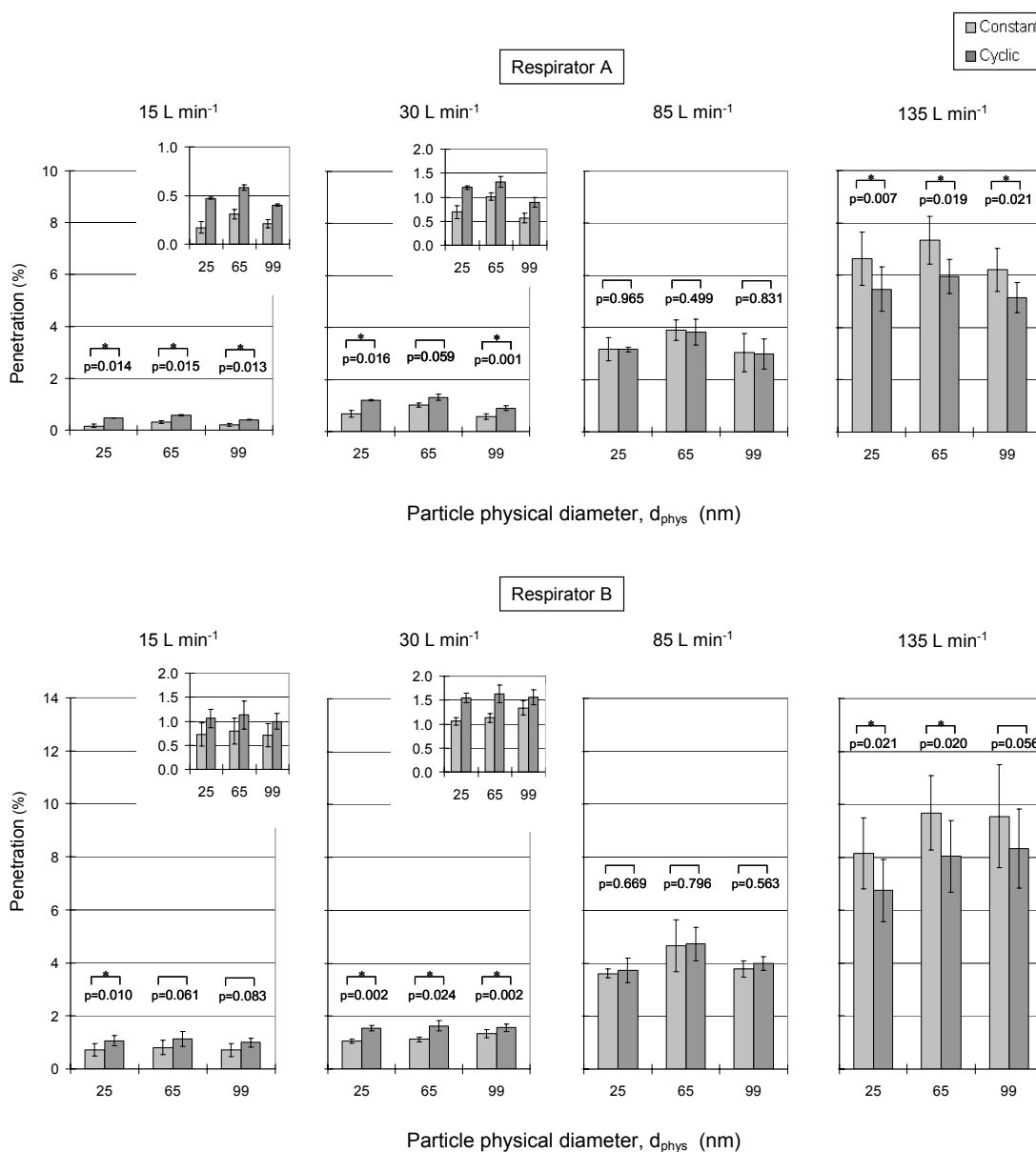


Figure 4. Penetration of PSL particles through the N95 respirators (A and B) at constant- and cyclic-flow conditions ($Q_{\text{const}} = Q_{\text{MIF}}$).

Particle Penetration (Theoretical Estimate)

To better understand and interpret the experimental findings, we performed an estimate of the particle penetration based on the advance filtration theory and information available on the physical characteristics of the tested FFPRs. We used a classic filtration theory (Hinds, 1999; Lee and Mukund, 2001; Gougeon et al., 1996) enhanced by including the electrostatic interaction governed by a polarization force that was calculated for uncharged particles and bipolarly charged fibers (Kanaoka et al. 1987; Lathrache and Fissan, 1986). The penetration fraction was calculated as

$$P = \exp\left(\frac{-4\alpha E_f L_f}{\pi d_f (1 - \alpha)}\right) \quad (3)$$

where α is the solidity or packing density, L_f is the filter depth, d_f is the fiber diameter, and E_f is the collection efficiency of a single fiber that can be calculated summing up the single fiber efficiencies due to specific mechanisms such as diffusion (E_D), interception (E_R), impaction (E_I), gravitational settling (E_G), and electrostatic interaction (E_q):

$$E_f = E_D + E_R + E_I + E_G + E_q \quad (4)$$

The diffusion component was determined as follows:

$$E_D = 1.6 \left(\frac{1 - \alpha}{Ku} \right)^{1/3} \frac{Pe^{-2/3}}{1 + 1.6(1 - \alpha/Ku)^{1/3} Pe^{-2/3}} \quad (5)$$

where Ku is the Kuwabara hydrodynamic factor

$$Ku = \frac{-\ln \alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4} \quad (6)$$

Pe is the Peclet number

$$Pe = \frac{U_0 d_f}{D} \quad (7)$$

U_0 is the air face velocity, D is the particle diffusion coefficient

$$D = \frac{K_B T C_c}{3\pi\mu d_p} \quad (8)$$

K_B is the Boltzmann constant, T is the fluid absolute temperature, C_c is the Cunningham slip correction factor, and μ is the fluid viscosity. The interception component was calculated as

$$E_R = \frac{1 + R}{2Ku} \left(2\ln(1 + R) - 1 + \alpha + \left(\frac{1}{1 + R} \right) \left(1 - \frac{\alpha}{2} \right) - \frac{\alpha}{2} (1 + R)^2 \right) \quad (9)$$

where R is the ratio of particle-to-fiber diameter. The efficiency of the particle impaction on a fiber

$$E_I = \frac{J(Stk)}{2Ku} \quad (10)$$

is a function of

$$J = (29.4 - 28\alpha^{0.62})R^2 - 27.5R^{2.8} \quad (11)$$

and

$$\text{Stk} = \frac{\rho_p d_p C_c U_0}{18\mu d_f} \quad (12)$$

with Stk being the Stokes number, ρ_p being the particle density. The single fiber collection efficiency due to gravitational settling is negligible for ultrafine particles (Hinds, 1999). Similar to the approach applied in an earlier study conducted by this research group (Balazy et al., 2006a), the electrostatic interaction between an initially uncharged particle and a bipolarly charged fiber of the FFPR's filter utilizing electret media can be quantified as follows:

$$E_q = B \left(\frac{1-\alpha}{Ku} \right)^{2/5} \frac{\pi N_{Q0}}{1 + 2\pi N_{Q0}^{2/3}} \quad (13)$$

The parameter N_{Q0} , defined as the ratio of electrostatic attraction force between an uncharged particle and a line-dipole charged fiber to the drag force, can be calculated as

$$N_{Q0} = \frac{C_c q^2 d_p^2}{(1 + \epsilon_f)^2 3\pi \epsilon_0 \mu d_f^3 U_0} \left(\frac{\epsilon_p - 1}{\epsilon_p + 2} \right) \quad (14)$$

where ϵ_p is the relative permittivity of fiber and ϵ_0 is the permittivity of the vacuum, ϵ_f is the permittivity of fiber, and q is the charge density of the fiber. The empirical constant B is introduced to allow for deviation of real structure from the ideal geometry of the Kuwabara cell model; $B=0.21$ was used by Balazy et.al. (2006a). The fiber charge density is usually an unknown parameter. By applying the best-fit method to the particle penetration data obtained for Respirator A, it was found that $q=13 \text{ nC m}^{-1}$ for that filter (Balazy et al., 2006a). Similarly, deriving from the best-fit method, we determined that $q=20 \text{ nC m}^{-1}$ for Respirator B. The above approach allows for an estimation of penetration under constant and cyclic flow conditions. In the former case, it is done by directly applying Eqs. (3) and (4) at a specific $Q=Q_{\text{const}}$. In the latter, P is calculated by accounting for the $P=f_Q(Q)$ and $Q=f_t(t)$ and integrating it within the inspiratory duration boundaries.

Particle Penetration (Comparison between Experimental and Theoretical Results)

For lower flow rates such as 15 and 30 L min^{-1} , the particle penetration values estimated using the above-described theoretical approach were found to be consistently lower than the respective experimental values, especially for smaller particle sizes. This held true for both the constant- and cyclic-flow regimes. However, the difference decreased with increasing flow rate. The comparison suggests that some uncertainties of the theoretical model can make it less than adequate for very small flow rates combined with very small particle sizes.

Relative Differences between Penetration Values Obtained under Two Flow Regimes (Experimental and Theoretical Data)

To determine relative differences in penetration for the two flow regimes, a $P_{\text{cyclic-to-}P_{\text{const}}}$ ratio was calculated for each set of conditions using experimental and theoretical data. The results for three particle sizes, four flow rates, and two respirators are shown in Table 1. At 85 L min^{-1} , the filter penetrations measured at constant and cyclic flows differ by only a few percent (and this difference is statistically insignificant). Significant differences were seen at the lower flows ($Q = 15$ and 30 L min^{-1}). The theoretical data demonstrate the same trends but revealed somewhat lower relative differences between P_{cyclic} and P_{const} . The differences were more pronounced for Respirator A, especially for the lowest particle size. An opposite trend (a slight overestimation) was observed at the highest flow rate of 135 L min^{-1} , but did not show significant dependence on particle size.

Table I. Ratio of Penetration Values Determined at a Cyclic and Constant Flow Regimes ($P_{\text{cyclic}}/P_{\text{const}}$). Each cell lists an experimental value of $P_{\text{cyclic}}/P_{\text{const}}$ as the mean $\pm$ standard deviation of 3 replicates (marked with an asterisk) as well as the theoretically value (double asterisk).

Respirator A

Physical particle size (nm)	Flow rate (L min ⁻¹)			
	15	30	85	135
25	3.04 $\pm$ 1.055* 1.86**	1.80 $\pm$ 0.356* 1.42**	1.01 $\pm$ 0.126* 1.09**	0.82 $\pm$ 0.002* 1.02**
65	1.92 $\pm$ 0.361* 1.42**	1.32 $\pm$ 0.151* 1.20**	0.98 $\pm$ 0.038* 1.03**	0.81 $\pm$ 0.028* 0.97**
99	1.94 $\pm$ 0.326* 1.42**	1.59 $\pm$ 0.170* 1.21**	1.00 $\pm$ 0.163* 1.04**	0.83 $\pm$ 0.023* 0.99**

Respirator B

Physical particle size (nm)	Flow rate (L min ⁻¹)			
	15	30	85	135
25	1.53 $\pm$ 0.293* 1.49**	1.46 $\pm$ 0.024* 1.23**	1.04 $\pm$ 0.123* 1.03**	0.83 $\pm$ 0.038 * 0.98**
65	1.45 $\pm$ 0.214* 1.30**	1.44 $\pm$ 0.118* 1.13**	1.03 $\pm$ 0.109* 1.00**	0.83 $\pm$ 0.045* 0.97**
99	1.49 $\pm$ 0.335* 1.33**	1.16 $\pm$ 0.019* 1.16**	1.06 $\pm$ 0.133* 1.02**	0.88 $\pm$ 0.031* 0.99**

The finding of this study – $P_{\text{cyclic}} > P_{\text{const}}$ obtained at lower flow rates – is consistent with the results reported by Brosseau et al. (1990) [although, unlike our test, the quoted study dealt with air purifying dust/mist respirators and larger (>100nm) particles]. Our data obtained at higher flow rates (85 L min⁻¹ or greater) can be, in principle, compared to those reported by Richardson et al. (2006) for N95 FFPR; however, the differences in actual filter face velocities and respirator models tested in our experiments and Richardson et al. study, respectively, do not allow for a direct comparison or, at least, make this comparison of limited validity..

The following interpretation was developed to explain the fact that, depending on the flow rate, the penetration of ultrafine particles through respirators under constant-flow conditions may be lower or higher than under cyclic-flow conditions. Filter penetration (P) is a non-linear function of face velocity and consequently of flow rate (Q). As flow increases (during the breathing cycle), the change in penetration described by a differential dP/dQ is represented by a non-monotonic function of the flow rate. The theoretical model predicts that at lower rates (up to ~10-30 L min⁻¹ for 20- to 100-nm particles), P increases slowly with increasing Q, but – at a certain flow rate level – begins showing more pronounced effect of P versus Q. This represents the area in which diffusion and electrostatic interaction (governed by the polarization force) are predominant filtration mechanisms. Further increase in the flow rate (above ~100 L min⁻¹) decreases the residence time, thus reducing diffusion deposition. We calculated the differential of penetration over the flow rate as $dP(\%)/dQ(\text{L min}^{-1})$ which represents the $P=f(Q)$ slope. As an example, these data are shown in Figure 5 for Respirator A. The differential reaches a maximum approximately between 70 and 85 L min⁻¹ for 65- and 99-nm particles. Then it slowly decreases with increasing flow rate. For 25-nm particles, the peak is observed at a higher flow (~100 L min⁻¹). Under a

cyclic-flow regime, the above-described complex dependence $P = f_Q(Q)$ translates into a similarly complex function of penetration versus time.

The sinusoidal breathing pattern shown in Figure 2 can be used to help understand the relationship concerning P_{cyclic} versus P_{const} . During inhalation, the cyclic air flow changes from 0 to 47.1 L min⁻¹ in the first 1.5 sec of the breathing period and then returns back to 0 over the next 1.5 seconds. The characteristic time of the zero-to-maximum change, $\frac{1}{4}T = 1.5$ sec, can be divided into three equal time intervals so that the first 0.5 sec corresponds to the flow rate increase from 0 to 23.6 L min⁻¹ (low flow time interval, further referred to as interval I), the second corresponds to an increase from 23.6 to 40.8 L min⁻¹ (middle flow interval - II) and the third one – to an increase from 40.8 to 47.1 L min⁻¹ in last 0.5 sec (high flow interval - III). While the penetration at a constant flow does not change over this 1.5 sec period, the penetration at the cyclic flow for each interval can be assessed through integrating $P = f_Q(Q)$ within this interval. Figure 6 presents the ratio of $P_{\text{cyclic}}/P_{\text{const}}$ for Respirator A at four flow rates and three particle sizes. The horizontal dashed line identifies a ratio of 1, which represents a situation where the same penetration values are obtained under constant- and cyclic-flow conditions. It is evident that for particles of 25 nm at $Q_{\text{const}} = Q_{\text{MIF}} = 15$ and 30 L min⁻¹, the P_{cyclic} -to- P_{const} ratio was considerably in excess of unity in region II and especially in region III, apparently making the overall value of P_{cyclic} also greater than P_{const} . This occurs because the higher flow rate within intervals II and III causes a less pronounced diffusional deposition. At 85 L min⁻¹, $P_{\text{cyclic}} < P_{\text{const}}$ during interval I is compensated by $P_{\text{cyclic}} > P_{\text{const}}$ during interval III; for interval II, the difference is almost non-existent. For particles of 65 and 99 nm, the influence of intervals II and/or III is lower at 15 and 30 L min⁻¹ than for 25-nm particles. It is seen that at 135 L min⁻¹, the difference between P_{cyclic} and P_{const} is primarily determined by interval I during which $P_{\text{cyclic}} < P_{\text{const}}$.

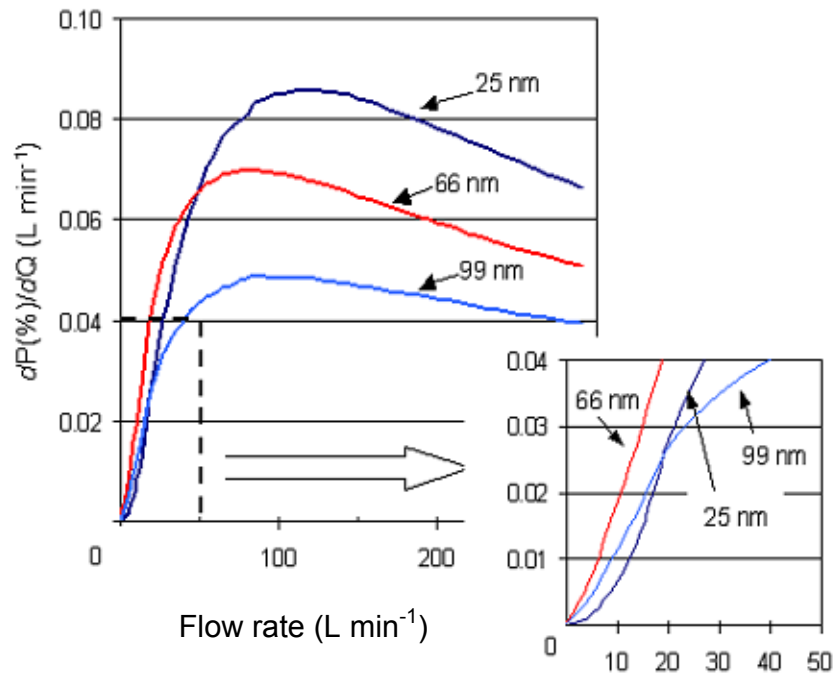


Figure 5. $dP(\%)/dQ(\text{L min}^{-1}) = f(Q)$: theoretical data for Respirator A.

Study Limitations

The present study is limited to a manikin-based protocol, in which the respirator is sealed on the manikin's face so that the particle may penetrate only through the filter media and not through the face seal leakage. Additionally, the cyclic flow is represented by a perfect sinusoidal function while in reality the breathing pattern is more complex. Finally, the influence, if any, of the reverse flow (mimicking exhalation) on the penetration was not evaluated. Given the objective of the study, the effects such as preconditioning and loading were not addressed. Also, it should be acknowledged that the tests were conducted only with two selected respirator models although numerous models of N95 facepieces are presently in use. However, both models consisted of electret-based filters, which are currently the most common materials in N95 FFPRs.

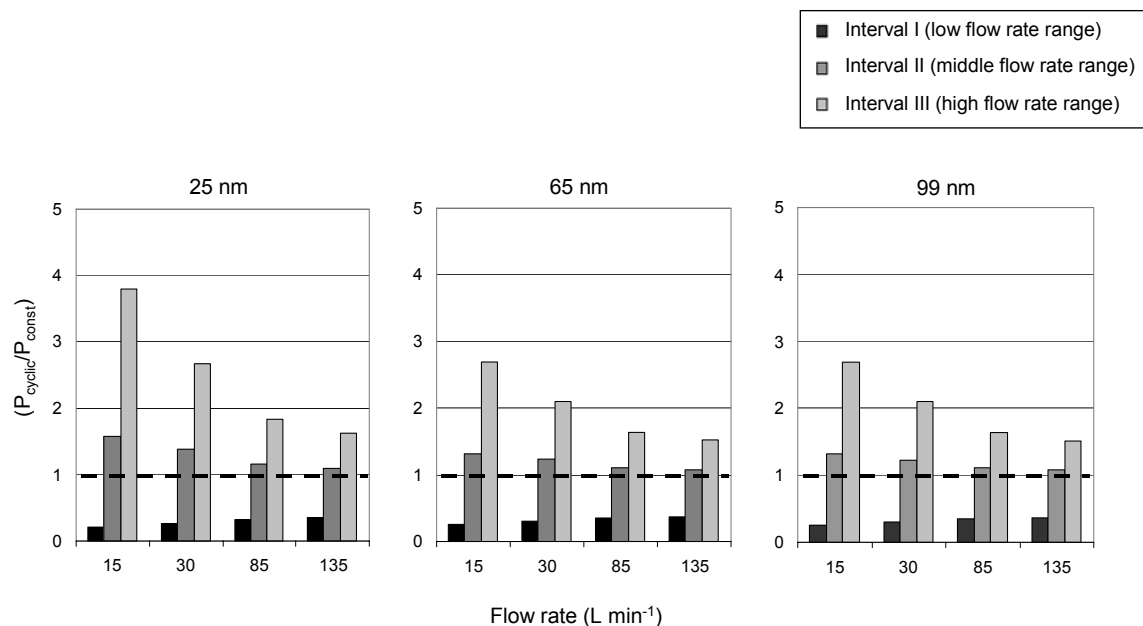


Figure 6. P_{cyclic}/P_{const} calculated for three equal time intervals (I, II, and III) within the time during which the flow rate under cyclic flow conditions increasing from 0 to Q_{PIF} .

CONCLUSIONS

In this study, we compared the performance of N95 respirator filters challenged with ultrafine particles under constant and cyclic flows. The study was conducted using two commercially available FFPRs with known filter characteristics to allow comparison between experimental and theoretical penetration values. The tests were performed at four flow rates (15 to $135\ L\ min^{-1}$) using three particle size fractions (25, 65 and $99\ nm$). The results indicate that tests performed with constant flow may not always be a good predictor of performance with cyclic flow. Depending on the flow rate, the penetration of ultrafine particles obtained under the constant-flow regime may be lower or higher than that obtained under cyclic flow. Statistically significant differences in the respirator filter penetration were found at 15 and $30\ L\ min^{-1}$ with P_{cyclic} exceeding P_{const} although essentially no difference was observed at $85\ L\ min^{-1}$ (the NIOSH certification flow rate) and a slightly reverse tendency was identified at $135\ L\ min^{-1}$. Fortunately, the current practice of using a constant flow for certification testing at $85\ L\ min^{-1}$ just happens to be predictive of cyclic flow having an equivalent mean inspiratory flow. The findings are supported and explained by

filtration theory for estimating the particle removal with FFPR fibers utilizing different mechanisms such as diffusion, electrostatic interaction, impaction, and interception. The experimental observations are attributed to a non-monotonic nature of $dP(\%)/dQ(L\ min^{-1})$ with a maximum reached at Q approximately between 70 and $>100\ L\ min^{-1}$ in the ultrafine particle range.

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