

Why Peak Flow Matters

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ABSTRACT

Peak flow rates developed during inhalation may have little effect on filter testing, but may still directly affect protection by influencing whether or not an uncomfortable respirator is worn when it should be. Subjective comfort may have a physiological basis related to the rate of respiratory work, flow wave shape, developed muscle pressures, and others. Peak inhalation flow rate contributes to each of these. For this reason, peak inhalation flow rates cannot be easily dismissed. Needs of human wearers are important factors contributing to protection.

Keywords: respirators, physiology, protection, comfort, frequency components

INTRODUCTION

What is the maximum flow rate inhaled by respirator wearers, and why is it important? The answer to the first part of this question has essentially been answered by a number of recently published papers (Berndtssen, 2004; Coyne et al., 2006; Janssen et al., 2005; Johnson et al., 2005B). Average peak flow rate measured by Berndtssen was 321 L/min, measured at about 90% $\dot{V}O_2$ max and while wearing air-purifying respirators. Janssen et al. measured a 95th percentile peak flow of 365 L/min for males at 80% $\dot{V}O_2$ max while not wearing respirators. Johnson et al. measured a 99th percentile measurement of up to 359 L/min and peak inhalation flow rate of 442 L/min at 80-85% $\dot{V}O_2$ max on unencumbered subjects. Conclusions reached from these studies are that: 1) peak inhalation flow rates for strenuous exercise are in the range of 350 L/min, and 2) peak flow rates last a very short time.

If peak flow rates represent only a very small fraction of inhalation flow rates, then Janssen concludes that there is little effect that these flow rates can have on filter protection (Janssen et al., 2005; Janssen, 2006). Indeed, he says, taking the respirator as a complete system means that there would be little effect on filter penetration whether or not the filter was designed to accommodate peak flows. Volumes of air inhaled during the short time durations of peak flows would not represent a significant health threat in any case.

Janssen makes a strong argument for discounting peak flow rate as compromising protection, and, if the only determinant of protection was the filter, then his position would likely be correct. However, it is widely recognized that respirators are considered to be very uncomfortable by a significant number of wearers (Johnson et al., 2005A; Bentley et al., 1973). It is these wearers who likely do not wear the respirators all the time they are needed (Aiba et al., 1995; Allsopp et al. 1997, Franco et al., 1998; Laird et al., 1993). Protection afforded by respirators requires them to be worn; it is time to consider the wearers as part of the system.

What makes respirators uncomfortable to the point where they are not worn? Obviously, a lot depends on the perceived nature of the threat. If the contamination level is low enough, and the health consequences are remote enough, then tolerance for respirator discomfort may not be so high. If the

respirator is removed, then it can't protect the worker. In this paper are explored several possible contributions that peak flow rates have on respirator discomfort, and, consequently, on protection.

RESPIRATORY ENERGETICS

Peak to average flow rate ratios differ with respiratory wave form, and actual values depend on the definition of "average." Average flow rate can be given for just the inhalation portion of the cycle (Janssen et al., 2005) or for the entire respiratory period (Johnson et al., 2005B). Assuming that inhalation duration is 50% of the respiratory period, these two definitions of time over which average flow rate is calculated give peak to average flow ratios that differ by a factor of two. Flow rate for a rectangular wave form is constant over the entire duration of inhalation. Therefore, the peak and average flow rates are equal, as long as the average is computed for only the inhalation portion of the breathing cycle. If the entire breath duration is used to compute the average flow rate, and if inhalation represents 50% of the breathing cycle, then peak flow is twice average flow. Thus, the peak to average ratios using only inhalation time give π , 2, 1, and 1-2 for sinusoidal, triangular, rectangular, and trapezoidal waveshapes, respectively, and 2π , 4, 2, and 2-4 for the same wave shapes with inhalation flow rate averaged over the entire respiratory cycle. These differences become even greater when the inhalation portion of the breathing cycle becomes smaller; inhalation approaches one-third of the respiratory period during extremely light work (Johnson, 1991; Johnson, 1999).

Janssen et al. (2005) compared peak to average inhalation flow rates (using only inhalation time) for data from a number of sources, and observed that peak to average flow rate ratios generally fall in the range of 2.5 to 3.8, with the ratios becoming lower with higher work rates, and ratios assuming higher values for women compared to men. Johnson et al. (2005B) measured peak to average flow rates (using the entire respiratory cycle time) at 2.7 for both sexes at very high work rates. This becomes 1.85 for inhalation flow rate only, assuming a 50% duty cycle. These values indicate that flow wave shapes tend toward trapezoidal or rectangular and away from sinusoidal.

It has been demonstrated that nonlinearities in the pressure-flow characteristics of both the respirator and the respiratory system, with pressure increasing disproportionately with flow rate, penalize flow wave forms with high peak to average ratios (Johnson, 1976). High peak flows cause high pressures and consequent high respiratory work rates. When inspiratory flow rates are closer to uniform, that is, when peak flow rates become less distinguishable from average flow rates, the work of breathing approaches the minimum possible at that value for average flow rate. Thus, rectangular breathing wave forms are more economical than any other breathing wave forms.

Johnson (1993) used a model of the respiratory system comprising resistance, compliance, and inertance elements. The resistance term was composed of a constant portion and a flow-dependent portion, as would be expected in any human respiratory system. He then computed the work of breathing for several standard flow wave shapes, including sinusoidal, rectangular, trapezoidal, exponential, and truncated exponential. Also included in the model was variable lung midposition observed during heavy breathing. The model was tested at light, moderate, heavy, and extreme rates of exertion. The rectangular wave shape was found to give the smallest work rate at any exertion level (Table I). For the heavy rate of exertion, penalties paid for the other waveforms (percentage increase above the minimum) were 8% for the trapezoid, 22% for the sine wave, and 23-24% for the exponential wave shapes.

Oxygen and nutrient substrates used to support respiration cannot be used directly to produce physical work. Only the skeletal muscles can do that. Thus, respiration, cardiac energy expenditure, neural activity, digestion, hormonal production, etc., can be considered support functions that contribute to the overhead of, but not directly to, physical work. It is not surprising, then, that these overhead functions, including respiratory work, are reduced as much as possible during heavy physical exertion.

Among the adjustments made in the respiratory system in response to the challenges of heavy physical exertion are changes in: 1) respiration rate, 2) ratio of inhalation time to exhalation time, 3) expiratory reserve volume (and lung midposition) 4) airway resistance (and dead volume), and 5) breathing flow wave form (Christie, 1953; Johnson, 1991; Otio et al., 1950; Silverman et al., 2005). Flow

wave forms normally adjust from sinusoidal at rest to trapezoidal during heavy exertion. Even with these adjustments, the percentage of the body's oxygen consumption devoted to respiration climbs from 1-2% at rest to 10% or higher during heavy exertion (Johnson, 1991).

Table I. Respiratory Work Rates (Nm/sec) for Five Different Inhalation Wave Shapes at Different Rates of Work

Wave Shape	Rate of Work				
	Rest	Light	Moderate	Heavy	Very Heavy
Sine	0.0832	0.228	1.85	4.57	7.93
Rectangular	0.0682	0.188	1.54	3.75	6.40
Trapezoid	0.0731	0.201	1.65	4.06	7.01
Truncated Exponential	0.1333	0.315	2.20	4.62	7.22
Hybrid Exponential	0.1203	0.294	2.12	4.64	7.46
Conditions					
Minute Volume (L/min)	8.00	15.0	50.0	80.0	110
Tidal Volume (L)	0.60	0.81	1.75	1.93	1.83
Waveform Duration (sec)	1.5	1.25	1.00	0.70	0.50
Initial Lung Volume (L)	2.21	2.12	1.80	1.74	1.77

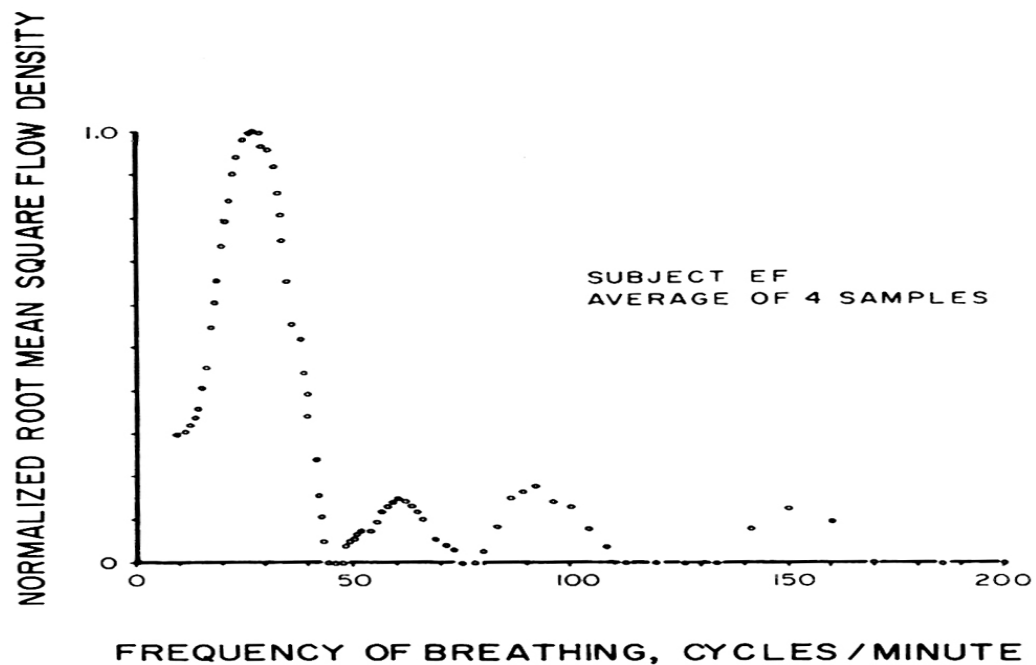
It has been shown both experimentally (Silverman, et al., 1951) and theoretically (Hämäläinen and Viljanen, 1978) that the addition of resistance to the breathing circuit induces the breathing wave form during exercise to become less sinusoidal, (and more rectangular) even at low to moderate work rates. Although not sinusoidal, the waveshapes are still rounded and quite different from unencumbered breathing wave forms. This indicates a tendency toward the most efficient breathing wave shapes under the imposed circumstances, despite an increase in the absolute level of respiratory work rate (Christie, 1953). The result of this is that a device such as a respirator that forces the (exercise) breathing wave form to change adds inordinately to the work of respiration and reduces the ability of the wearer to accomplish physical work. Of course the resistance, compliance, and dead volume added to the respiratory system by the respirator would, by themselves, add significantly to the respiratory work burden, but the tendency to change the flow wave shape adds to the burden.

FREQUENCY COMPONENTS

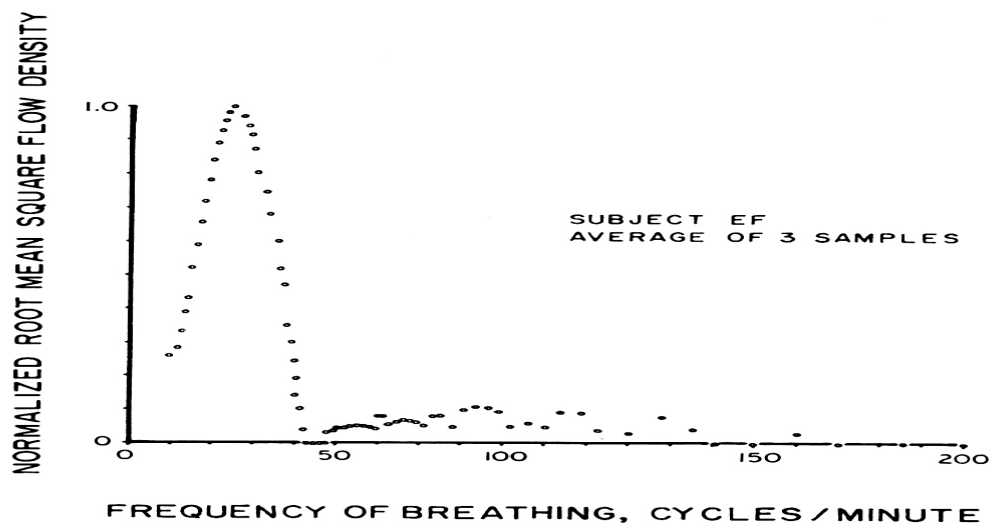
Peak flow rates exist for very short durations of time and constitute less than 1% of the flow rates measured during breathing (Johnson et al., 2005B). They represent rapid rates of change of flow rate, and this corresponds to high frequency components of flow in the frequency domain.

Mechanistically dominant characteristics of the respirator are its resistance and compliance. Because of these, the respirator acts as a mechanical low-pass filter on the respiratory system. The effect of this property is that high-frequency components of flow are reduced or eliminated.

Johnson (1972) measured frequency components of the breathing waveform with and without a U.S. Army M17 air purifying respirator. As can be seen from Figure 1, higher frequency components were attenuated relative to lower frequency components when a respirator was worn.



1a



1b

Figure 1. Harmonic content of breathing flow wave forms without (1a) and with (1b) a U.S. Army M17 air purifying respirator. The ordinates of the figures plot the root mean square values of the power spectral density of breathing wave form samples. These have been normalized so that the magnitudes of the fundamental frequency with and without the respirator are both the same. There is clearly identifiable harmonic content without the respirator that is not present during respirator wear. From Johnson (1972).

Sine waves have one frequency, and only one. Other wave forms can be decomposed into a series of sinusoidal components, and hence can have more than one frequency component. The rapid changes of flow at the beginning and end of a rectangular wave shape, for instance, represent very high frequency components. The constant interval in the middle of the rectangular wave is represented by low frequency components. Removing the high frequency components and retaining the low frequency components transforms the rectangular wave form into a shape more like a sinusoid.

Removing the high frequency components from a rectangular wave and producing a more sinusoidal wave shape requires respiratory adjustments if the same tidal volume is to be maintained. The volume accumulated in a rectangular waveform is just ($\dot{V} \max t_{inh}$). The volume accumulated in a sine wave of equal maximum amplitude and duration is ($2\dot{V} \max t_{inh} / \pi$), or only about two-thirds as large as with the rectangular wave. Even without nonlinear resistance components in the respirator and respiratory system, extra respiratory effort must be exerted in order to maintain tidal volume while wearing a respirator. Tidal volume while wearing a respirator appeared to be greater than without a respirator for low intensity work rates but smaller with a respirator at high rates of work (Johnson et al., 1995B). Unpublished observations have shown tidal volume to decrease with breathing resistance increase across all work rates. Therefore, breathing resistance is likely to cause change in tidal volume.

It has been demonstrated that minute volume with the respirator cannot be maintained at its unencumbered level (Johnson et al., 1995B; Johnson et al., 1999). Hypoventilation accompanies respirator wear (Figure 2) at all work rates and the effect is more pronounced for higher breathing resistances. One reason for hypoventilation may be the loss of high frequency components from (otherwise unencumbered) flow wave shapes that appear more like trapezoids than sinusoids at high exertion levels (Figure 3).

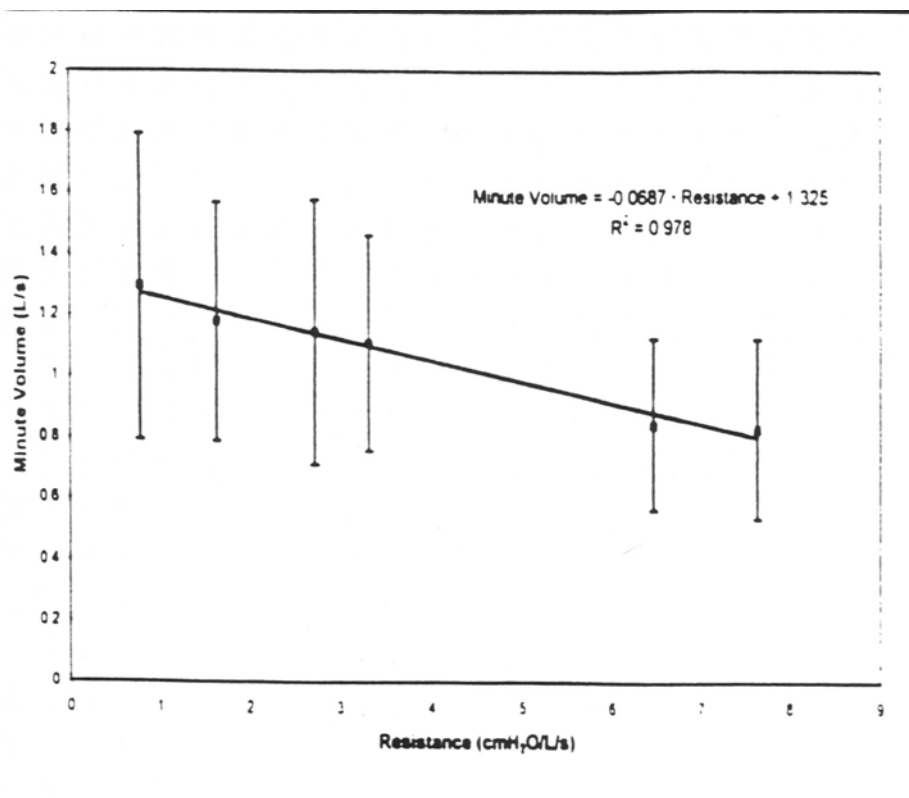


Figure 2. Minute ventilation decreases linearly with increase in respirator inhalation resistance (Johnson et al., 1999).

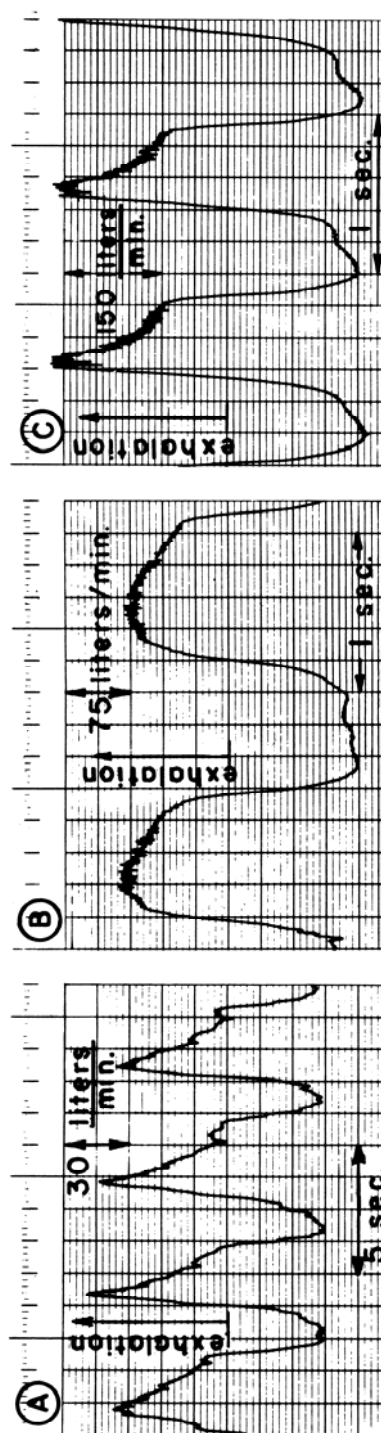


Figure 3. Respiratory flow wave shapes change with exertion level when not wearing a respirator (Johnson, 1991).

Another penalty for removal of high frequency components is that the respiratory system is likely to attempt to maintain those components by increasing pressures. We are unfamiliar with data that relates respiratory muscle pressures to frequency in the respiratory system. However, it is likely, based on the fact that rapid shortening of muscle fibers is less economical than slow contraction (Johnson, 1991), that extremely high effort would have to be employed in order to attempt compensation for the loss of high frequency components (Figure 4; Lausted et al., 2006). As lung volume changes, so does maximum developed pressure.

It had previously been demonstrated that dyspnea, or the feeling of respiratory distress, was related to the ratio of pressure developed in the respiratory system to the maximum pressure that could be developed (O'Connell and Campbell, 1976). It is not hard to deduce, then, that reduction of high frequency components from the respiratory wave form could lead to higher pressures developed at those frequencies, and that these pressures, in turn, would elicit feelings of respiratory distress over a significant portion of the inspiratory phase of the breathing cycle.

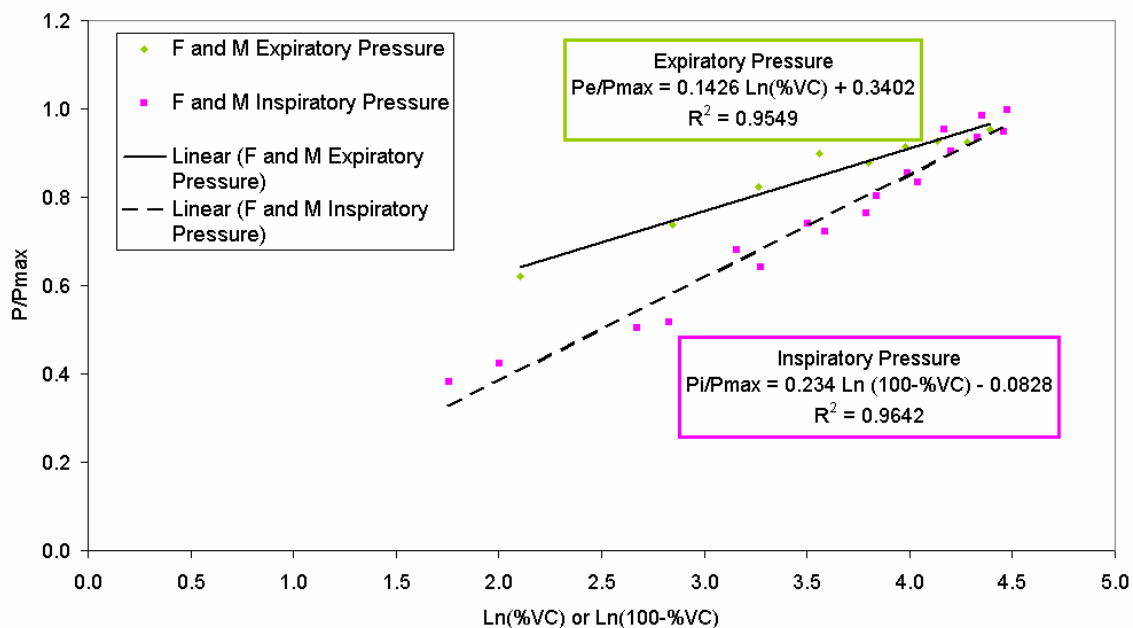


Figure 4. Maximum pressures developed in the respiratory system depend upon lung volumes. The highest inhalation pressure occurs at the lowest lung volume and the highest pressure in the exhalation direction occurs at the highest lung volume (Lausted et al., 2006). F and M denote female and male, respectively.

FACEPIECE CONFIGURATION

Rebar et al. (2004) studied the effects of facial characteristics on inhalation and exhalation resistances experienced by wearers of respirator masks. There was about a two-fold range of resistances experienced by different wearers of the same respirator masks. There were no discernable relationships found between resistances and anthropometric measurements made. Therefore, there was no good reason to which the different resistance levels could be attributed.

It is known, however, that energy is required to change the magnitude or direction of flowing fluid (Johnson, 1999). The air inside the respirator is no exception. There are regions of flow constriction and induced turbulence (Johnson and Cummings, 1975). Facial configuration and the fit of the mask facepiece can affect these areas, and it is unlikely that simple anthropometric measures would be able to completely determine facepiece-face compatibility.

Higher respiratory flow rates can affect pressure drops within the facepiece and thus affect apparent resistances. Peak flow rates produce peak pressure drops, and it appears that the fit of the respirator to the face may have a large impact on pressure drops. Some people may be affected more than others.

OTHER POSSIBLE INFLUENCES

There are many small irregularities in flow rates during the breathing cycle, and their causes are not known. Some may be related to oscillations in the respiratory system, and some may be related to impacts when the feet strike the ground while walking. Neither of these has been recognized as obvious, and there are still many flow perturbations seemingly unrelated to external events.

At least some recorded peak flow measurements were probably of a random nature, some of the unexplained irregularities. Most, however, were regular enough to contribute to an unexpectedly high R^2 value of 0.9 in a regression relating peak to average flow (Johnson et al., 2005B; see also Caretti et al., 2006).

The question still remains about whether reduction or removal of small irregularities contributes to a feeling of respiratory discomfort. No definitive answer can be given at this time. On the one hand, the case has already been made that removal of high frequency components is likely to be noticeable to the wearer. On the other hand, there may be a large difference between high frequency components that contribute to the general breathing flow wave shape and those that don't.

Another possible contributor to respiratory discomfort is personality trait. To a limited extent, personality has been found to affect performance times while exercising wearing respirator masks (Koh et al., 2006; Francis, 2006). It is possible that certain personality traits or inclinations may exacerbate feelings associated with non-normal respiration, and contribute to feelings of unease. It is known that some people tolerate respirator wear more than others (Koh et al., 2006; Johnson et al., 1955B; Morgan and Raven, 1985) and it is known that familiarity with respirator wear improves tolerance (Francis, 2006). So, it is possible that unsatisfied peak flow requirements can have different results for different people.

DISCUSSION

Respirator comfort is an oxymoron. Only under very unusual circumstances could a respirator be called comfortable. But respirator masks should be wearable, which is to say that they should be able to be tolerated without undue accommodation by the wearer.

Aiming for wearability requires that the human wearer be considered in the design process. The human has needs that must be recognized. It is often much easier to design a device such as a respirator without accounting for its total effect on the human user than to try to design around the needs of the wearer. The result, therefore, is a device that performs some of its functions very well and some poorly. In the case of respiratory protective masks, they can filter contaminants very well and can theoretically protect against high levels of atmospheric toxins. In actual use, however, some respirators are not worn or are worn incorrectly. So, theoretical protection offered by these respirators is compromised even to the point of nonexistence.

There is documentation that respirators are not always worn when they are supposed to be. Laird et al., (1993) indicated that 15% of their respondents in a wide range of industries said that they did not wear their required respirators. Nearly two-thirds of the respondents stated that they removed the respirator or some reason before completing the work that required its use. Twenty two percent of

Japanese lead workers used unauthorized dust respirators, and 73% used a knit cover (Aiba et al., 1995). Dental hygienists were reported to use respiratory protection against dental aerosols very sparingly (Allsopp et al., 1997). Franco et al. (1998) observed surface miners in western Pennsylvania wrapping old undershirts around their faces instead of using required respirators. Only 45% of 660 miner volunteers reported using their own or a company-provided respirator. Of these, only 41% reported using the respirator at all or most of the time when exposed to dust. Thirty-one reported interfering facial hair. Consequently, 7% of drillers employed less than 10 years, 30% of drillers employed 10-20 years, and 61% of drillers employed more than 20 years expressed silicosis-like symptoms.

In this paper has been shown some evidence that peak flow rates could matter when respirators are worn, especially at high work rates. The fact that many wearers continue to use respirators under conditions where other wearers are likely to doff their respirators points to the likely conclusion that wearers are individuals with individual sensitivities and reactions. Not everyone is likely going to be affected by changes in respiration imposed by protective devices. There are some, however, who may be affected a great deal. As with any mass-produced product, respirators may be designed for the most sensitive wearer, or for the least sensitive. The trend for other products is to design to accommodate as many special needs as possible.

Janssen was probably correct when he said that peak flow rates are of little to no consequence in filter testing. However, the rest of the story is that peak flow rates are likely to be important in overall protection afforded by a respirator. This is when the respirator is paired with a wearer—both parts must work together.

CONCLUSIONS

Peak flow rates developed during inhalation may have little effect on filter testing, but may still directly affect protection by influencing whether or not an uncomfortable respirator is worn when it should be. Subjective comfort may have a physiological basis related to the rate of respiratory work, flow wave shape, developed muscle pressures, and others. Peak inhalation flow rate contributes to each of these. For this reason, peak inhalation flow rates cannot be easily dismissed. Needs of human wearers are important factors contributing to protection.

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