Minute Volumes and Inspiratory Flow Rates During Exhaustive Treadmill Walking Using Respirators

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Air flow rate through filters and face masks is one important determinant of the final protection factor of a respiratory protective device in use. Respiratory minute volumes and instantaneous breath flow rates were measured in eight subjects during treadmill work using three types of filtering respirators and one control breathing mask. Work comprised five consecutive bouts of walking at 5 km/h with an increase in elevation of the treadmill by 5% every 5 min and a final walk at 6 km/h and 22.5%. Three subjects managed to complete 5 min at the final work rate. Minute ventilation increased in a curvilinear manner with oxygen uptake and reached 88 ± 20 and 93 ± 20 l/min at 5 km/h (20%) with the control mask and a half mask with filter (SP), respectively. Mean peak inspiratory flow rate (PIFR) was 273 ± 39 for Control and 300 ± 36 for SP at the same work rate. Two power assisted, positive pressure filter respirators (SA and SE) produced higher mask minute volumes at any given work rate compared to respiratory minute volumes in control and SP. PIFR in SA and SE were equal to or lesser than SP. During standardized speech communication, minute volumes decreased. In contrast, PIFR increased by about 100% at low work rates and about 30% at 5 km/h (20%) compared to no speech condition, reaching a highest value of 414 ± 46 l/min for SE. Filter testing is made at a constant flow rate of 95 l/min, a condition that eventually needs to be reconsidered in order to ensure a relevant and valid function test.

Keywords: exercise; metabolic rate; oxygen uptake; peak flow rate; ventilation

INTRODUCTION

Respirators are commonly used to reduce the inhalation of hazardous substances in contaminated atmospheres. The final protection offered by the equipment is determined by inherent properties of the filters, the face mask and the equipment design, but also by factors, such as fit, size and movements. One of the important factors for the evaluation of protection is the air flow volumes and air flow rates charging the equipment during use. Light work, at an oxygen uptake at about 1 l/min, requires a minute ventilation of about 30 l/min. At higher levels of activity, for example associated with fire fighting and rescue and emergency operations, much higher minute volumes are experienced (Clare et al., 2004; Holmér et al., 2006; Lusa et al., 1993; Smith et al., 2001). Certain types of respirators are not suitable for use in these conditions. Increased breathing resistances reduce performance (Caretti and Whitley, 1998; Caretti et al., 2001; Heus et al., 2004; Johnson et al., 1999; Jackson et al., 2002). Technical development, such as filters with lesser breathing resistance and power assisted respirators, allows more heavy work and longer work periods without unacceptable physiological strain (Berndtsson, 2004). For design of such equipment and for assessment of the final protection offered by the equipment, the respiratory load and the associated air flow dynamics of the breathing cycle must be known.

Filters are tested for penetration at a constant air flow rate of 95 l/min (EN-143, 2000). Breathing resistances of full face masks and half masks are tested on a breathing machine set at 25 strokes of 2 l, providing a peak flow rate of 160 l/min (EN-136, 1998; EN-140, 1998). Such a flow rate would be expected for only a fraction of the breath during light work and minute ventilation at around 30–50 l/min. Silverman et al. (Silverman et al., 1951) reported already in 1951 that peak flow rates during the breath cycle at higher work rates could exceed 4–5 l/s (240–300 l/min). This
methods and procedure

Eight subjects (7 males and 1 female) volunteered for the study. The mean and SD were for age 36 ± 3 years, weight 80 ± 11 kg and height 178 ± 9 cm. They were informed about purpose, measures and procedures before giving their consent to participate. The study was approved by the ethics committee of the university.

At their first visit to the laboratory they performed a 25–30 min exercise test on a treadmill in a climatic chamber kept at 22°C and 30–40% relative humidity. The test was intended to provide an incremental workload that would end in a maximal effort by the subject. Test was ended voluntarily by the subject at the point of exhaustion when he or she could not maintain walking speed. Subjects were dressed in t-shirt, shorts, socks and jogging shoes.

The exercise test comprised walking at 5 km/h on a treadmill for consecutive periods of 5 min. During the first 5 min the incline of the treadmill was 0%. After every 5 min the incline was raised by 5%. All subjects completed walking at 5 km/h and 20% inclination. Five subjects also managed 1–5 min at 6 km/h and 22.5% inclination. At the end of the exercise each subject was at or near maximal exhaustion. During the final minute of each work period, the subject read a standard text with loud voice at his or her preferred speed. The test described in detail the procedure of the experiment and was familiar to the subject. The subject was asked to speak so loud that it could be heard and understood by the experimenter outside the chamber via the communication system.

The different respirators did not appreciably affect the background noise level.

Oxygen uptake, minute ventilation and air flow rates were measured with Metamax 1 (Cortex, Germany). Special software modules for metabolic measurements were used. The flow meter of the Metamax is a turbine with a sampling frequency of 25 Hz. The equipment is intended for portable use, but compares favourably with standard laboratory equipment (Schultz et al., 1997). Heart rate was measured with chest electrodes and radio transmission using the Polar system (Polar Electro, Finland). Measurements were continuously monitored and recorded during 3–4 min (no speech) and 4–5 (speech). The average of the last 30 s of each minute was used for the analysis. As it was not possible to measure the oxygen uptake in the respirator tests the values obtained for each individual in this first test was used as a measure of the energetic work load for all conditions.

The peak oxygen uptake for the subjects measured during this first experiment (Control) averaged 4.15 ± 0.67 l/min (STPD). The metabolic rate was calculated from the VE based on the following formula (ISO-8996).

\[
M = \frac{V_{O_2} \cdot 60 \cdot 5.82}{A_D} = \frac{V_{O_2} \cdot 349}{A_D}
\]

where \(M\) is the metabolic rate in W/m², \(V_{O_2}\) is the oxygen uptake in l/min, \(A_D\) is the body surface area in m² and 5.82 is the energy equivalent of oxygen from measured RQ-values in Wh/l O₂. Individual values for \(A_D\) was determined by the DuBois formula (DuBois and DuBois, 1915).

In three consecutive experiments the same exercise test was repeated with subjects wearing and breathing through three different types of filtering respirators. Tests were randomly distributed and performed with one week’s interval. The respirators are described more in detail in Table 1. Respirator SP is a traditional passive filter mask that produces a negative pressure inside the face mask during the inhalation phase. It uses one filter mounted in front of the face mask. SA and SE are powered filtering devices consisting of a full face mask that is connected via a tube to a box carried on the waist. The air is sucked by a fan into the

<table>
<thead>
<tr>
<th>Condition</th>
<th>Equipment</th>
<th>Mask</th>
<th>Filter</th>
<th>Function</th>
<th>Flow rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Metamax, Cortex Germany</td>
<td>Half mask</td>
<td>No filter</td>
<td>Negative pressure</td>
<td>—</td>
</tr>
<tr>
<td>SP</td>
<td>Sundstrom Safety, Sweden SR100</td>
<td>Half mask, exhalation valves</td>
<td>Particle filter in a filter house</td>
<td>Negative pressure</td>
<td>—</td>
</tr>
<tr>
<td>SA</td>
<td>Sundstrom Safety, Sweden SR500</td>
<td>Full face mask, exhalation valves</td>
<td>Two particle filters</td>
<td>Positive pressure, power assisted</td>
<td>175 and 225 l/min</td>
</tr>
<tr>
<td>SE</td>
<td>S.E.A. Safety Equipment Australia SEA400</td>
<td>Full face mask, exhalation valves</td>
<td>Two particle filters</td>
<td>Positive pressure, power assisted</td>
<td>Demand controlled</td>
</tr>
</tbody>
</table>
box through two standard filters and supplied via the tube to the face mask. The system creates a positive pressure inside the mask that eventually is maintained even at high inspiratory efforts. SA works at two fixed flow rates that can be set by the user (175 and 225 l/min). SE provides a flow rate that is controlled by the respiratory demand.

In the three tests with respirators, minute ventilation and flow rates were measured during the inhalation cycle. This was done with a special flow meter constructed by an instrument manufacturer (SWEMA, Stockholm, Sweden). The sensor of a standard velocity meter (SWA32) is mounted in the middle of a 10 × 3 cm open-ended tube. The tubular flow meter is calibrated by the company against defined flow rates. SWEMA is a certified national center for calibration of air velocity instruments. This flow meter was compared with the turbine flow meter of the Metamax system and of the SEA respirator and found to give almost the same values over the full range of measurements ($R^2$-values of 0.99 or better in both cases).

The flow meter tube was placed as close to the face mask as possible. Adapters were constructed so that the tube could be connected to the inhalation opening of the mask. The other side of the tube was fitted to the tube leading to the filter house (SE and SA) or ended in free air (Control). For SP an adapter was made that allowed connection to the filter holder in front of the mask.

The new flow meter was required to allow sampling during the inhalation phase. For the Control and SP face masks the true respiratory minute ventilation ($V_E$) is measured, as breathing is driven solely by respiratory muscle work and regulated by metabolic demands. With SE and SA excess air is provided by the respirator fan, basically to create a positive pressure in the face mask. The measured flow rate integrates these two sources of air flow. This flow rate is defined as the mask minute ventilation. The same conditions apply for the measured peak flow rates.

The flow meter recorded air flow rates through the tube at 10 Hz. Accordingly during 4 and 5 min about 600 measures, respectively, of the instantaneous, inhalation flow rate was recorded. For each minute (4 and 5) the second part (30 s) was evaluated. For each breath during 30 s a highest inhalation flow rate was measured and the average, defined as mean peak inspiratory flow rate (PIFR), was calculated. The highest value for all the breaths during the period was defined as the maximal PIFR. This single value was on the average 10% higher than the mean PIFR during the minute. All minute volumes and flow rates are given in BTPS. Values generally reported here are the mean PIFR. Flow rates only refer to the inhalation phase. During exhalation the flow meter indicated zero or constant values (see Figures 4 and 5). This enabled an accurate determination of the time of the inhalation and exhalation phases.

**RESULTS**

Oxygen uptake increased with inclination of the treadmill (Figure 1). All subjects completed 5 min at 5 km/h and 20% inclination. For three subjects this was maximal work and they stopped due to exhaustion. The average oxygen uptake at 5 km/h and 20% was 3.36 l/min (Table 2). Two subjects continued a few minutes at 6 km/h and 22.5% until exhaustion. Another three subjects completed also this activity for 5 min, but admitted that they were close to exhaustion. For three of the subjects oxygen uptake was higher than 4 l/min when they stopped (Figure 1).

Respiratory minute ventilation ($V_E$) was almost linearly related to oxygen uptake (Figure 2). The best equation fit to data is by a power function; $V_E = 21.6 \times V_O2^{1.6}$, $R^2 = 0.99$. Three subject’s data for the highest activity level are included in the regression analysis. The equation, however, was very similar even if these data points were excluded.

Minute volumes for all four respirator conditions in relation to control oxygen uptake values are presented in Figure 3. Minute volumes for control and SP conditions are similar and represent true respiratory minute volumes. For SA and SE the values represent minute volumes for mask flow rates. The higher flow rates for given oxygen uptake is a combined result of the inspiratory effort and the forced air flow into the mask by the blower of the respirator. For SA the blower was set at 175 l/min for the two lowest workloads and at 225 l/min for the others. SE has a system that controls the flow rate in relation to respiratory demand.

Figures 4 and 5 shows the records of respiratory flow rates during test with SP and SA in one subject. Values are given for 4 min (no speech) and 5 min (speech) for all workloads. It is readily seen that peak

![Fig. 1. Oxygen uptake and metabolic rate in relation to work for eight subjects (3 at 6/22.5).](image-url)
flows are generally higher during the speech minute than during no speech. The difference becomes smaller at higher workloads. This subject was able to complete 5 min at the highest work rate. PIFR changes from about 100 l/min at the lowest work rate to just below 400 l/min at the highest. During talk PIFR changed from about 200 l/min to about 450 l/min (Figure 4).

The breathing pattern and flow rates are different for the power assisted filter respirator (Figure 5). A constant flow rate to the mask of either 175 or 225 l/min reduces both the magnitude of PIFR and the difference between no talk and talk conditions. PIFR during the two conditions are about 100 l/min lower than with the passive device (SP) at the highest work rate (Figure 4).

Figure 6 show PIFR in relation to \( V_{O_2} \) for the three respirators and control. PIFR increases in a curvilinear manner for SP and SE with \( V_{O_2} \). With SA PIFR increases more slowly with increasing workload. Regression analysis with a power function gives a \( R^2 \)-value of 0.95 or higher for all conditions.

Table 2. Mean values and 1 SD for measured parameters for 5 km/h and 20% inclination for the three respirators and control conditions

<table>
<thead>
<tr>
<th>Subjects</th>
<th>( V_{O_2} ) (l/min) STPD</th>
<th>( V_{O_2} ) ml kg(^{-1} ) min(^{-1} )</th>
<th>M (W/m(^2))</th>
<th>( V_p ) (l/min) BTPS</th>
<th>Mean insp. flow rate (l/min) BTPS</th>
<th>PIFR l/min (l/s) BTPS</th>
<th>PIFR l/min (l/s) BTPS speech</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controls</td>
<td>3.36</td>
<td>42</td>
<td>582</td>
<td>88</td>
<td>194</td>
<td>273 (4.6)</td>
<td>373 (6.2)</td>
</tr>
<tr>
<td></td>
<td>0.49</td>
<td>2</td>
<td>89</td>
<td>20</td>
<td>50</td>
<td>39</td>
<td>53</td>
</tr>
<tr>
<td>SP</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>93</td>
<td>192</td>
<td>300 (5.0)</td>
<td>407 (6.8)</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>20</td>
<td>43</td>
<td>36</td>
<td>48</td>
</tr>
<tr>
<td>SA</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>208</td>
<td>266</td>
<td>281 (4.7)</td>
<td>346 (5.8)</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2</td>
<td>6</td>
<td>16</td>
<td>45</td>
</tr>
<tr>
<td>SE</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>150</td>
<td>226</td>
<td>309 (5.2)</td>
<td>414 (6.9)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25</td>
<td>34</td>
<td>36</td>
<td>46</td>
</tr>
</tbody>
</table>

For all three respirators PIFR depends strongly on the mask minute ventilation (Figure 7). Regression analysis with a power function gives a \( R^2 \)-value of 0.99 for all except SA (0.83). A given PIFR value, however, is achieved at different minute ventilations. A PIFR of 300 l/min (5 l/s) is achieved at a minute ventilation of about 90 l/min for Control and SP, at 145 l/min for SE and about 210 l/min for SA.

During the respiratory minute volumes are generally lower during speech at a given workload. Despite this PIFR is higher at a given minute volume in comparison with no speech (Figure 9). The absolute highest values for PIFR are also reached during speech; although the values for the power assisted respirators
(SE and SA) are only slightly higher than for no speech condition. Regression analysis with a power function reveals $R^2$-values higher than 0.97 for all except SA (0.84). The exponent is 0.50 and 0.59 for control and SP, respectively, and 1.68 and 2.1 for SA and SE, respectively.

Table 2 shows results for the final work period that all eight subjects completed (5 min at 5 km/h, 20% grade). Oxygen uptake at this activity level was 3.36 l/min. Corresponding metabolic rate was 582 W/m². Minute ventilation was 88 l/min. Values for $V_E$ and PIFR for all conditions are given. Mean inspiratory flow rate is about two times higher than $V_E$ except for Control and SP, where it is only slightly higher. For SA and SE values are similar but only 1.3–1.5 times higher.

The mean PIFR was around 300 l/min (5 l/s) for all four conditions without speech. During speech PIFR was generally 25–35% higher and highest for the SE conditions. The highest individual PIFR during any
30 s sampling period was 552 l/min (9.2 l/s). This was measured with SE during speech at the highest work rate (6 km/h and 22.5% inclination).

The four different respirator devices provided for different flow rates in the mask. In conditions without power assisted breathing (Control and SP) PIFR is 3–3.5 times higher than \( V_E \) without speech (Figure 10). During speech the ratio changes from about 10 at low work rates to 4 at high work rates (Figure 11). For the power assisted respirators the ratio is much lower (Figures 10–11).

Inhalation time in percent of total breath time is given in Figure 12. During no speech condition the inhalation time is 45–65% of the breath cycle. During speech the inhalation is shortened to around 20% at low activity rising to about 40% at the highest activities. Figure 13 shows the percent of the inhalation time that air travels faster than 95 l/min. This value varies from <20% for SP at the lowest activity level to 100% for SA. In general the percentage values are higher during conditions of speech.

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**Fig. 6.** PIFR in relation to oxygen uptake measured in the control condition for the three respirators.

**Fig. 7.** PIFR in relation to measured mask minute volume for all conditions without speech.

**Fig. 8.** PIFR in relation to measured oxygen uptake in the control conditions for the three respirators during speech.

**Fig. 9.** PIFR in relation to measured mask minute volume for the three respirators during speech.

**Fig. 10.** Ratio of mean PIFR to mask minute volume in relation to mask minute volume for no speech conditions.
DISCUSSION

Respiratory minute ventilation for the Control condition is directly related to oxygen demand during physical work and increases linearly or in a curvilinear manner with oxygen uptake. The values are of the same magnitude as reported in other studies (Berndtsson, 2004; Holmér and Kuklane, 2002; Johnson et al., 1999; Kaufman and Hastings, 2005; Holmér and Gavhed, 2007; Caretti and Coyne, 2006). The highest value was 159 l/min (BTPS) for one subject at 6 km/h (\(V_O_2 = 5.21\) l/min, STPD).

Filtering respirators, in particular, negative pressure devices comprise higher breathing resistances than during normal, unmasked breathing and might result in hypoventilation, at least at higher work intensities (Caretti and Whitley, 1998; Johnson et al., 1999; Caretti et al., 2001). This was not seen in our results comparing control with SP. Only at the highest work rate (with three subjects) \(V_E\) was lower in SP. One explanation can be that a particle filter does not create that much breathing resistance compared to a gas filter or a combined filter. Another explanation can be that subjects in this study were quite fit and, therefore, may easier overcome the additional strain on respiratory muscles.

The power assisted respirators (SA and SE) create a positive pressure in the face mask and facilitate breathing. The minute ventilation measured with these respirators is mask minute ventilations rather than respiratory minute ventilations. Measured minute volumes, however, pass through filters, mask and valves and are still relevant figures for the analysis of the loads on the system and its performance efficiency. Mask minute ventilations are much higher than \(V_E\) for control and SP conditions at any given work rate \((V_O_2)\), particularly for SA that provides a constant flow of either 175 or 225 l/min.

The mean value of PIFR for eight subjects at high work rate (Metabolic rate = 582 W/m\(^2\) and \(V_O_2 = 3.36\) l/min) was almost the same for all conditions or about 300 l/min (6.0 l/s) without speech and about 400 l/min with speech (Table 2 and Figures 6–9). At low work rates they were also similar during speech (Figures 8–9), but higher in general for the powered respirators (Figure 6–7).

PIFR was highest at all work rates with SE. This may be explained by the way respiration is assisted. With SE the flow rate provided by the blower is demand controlled, which means that the blower accelerates within each breath cycle to provide a defined flow rate. With SA a constant flow is provided irrespective of the demand, which results in much smaller variation in PIFR with work rate but also in lower values at high work rates.

Our values for SP compare favourably with compiled data from four different studies reported by Caretti et al. (Caretti and Coyne, 2006). The review...
included also results from studies at near maximal to maximal work rates.

Berndtsson (Berndtsson, 2004) reported similar results from measurements on subject’s during incremental bicycle exercise with passive filter respirators, although his subjects did not reach as high activity levels as in this study.

Kaufman and Hastings (Kaufman and Hastings, 2005) measured high-PIFR values during simulated emergency work procedures. At the highest work rates PIFR was on the average 239 l/min (32 subjects) with individual values often exceeding 300 l/min.

For passive, negative pressure respirators PIFR appears to be 3–3.5 times higher than $V_E$. This is close to the value of pi (3.14) that would be expected for a sinusoidal breathing curve. Breathing pattern becomes different when a power assisted respirator is used. The mask flow rate is higher at any given work rate. The constant flow respirator (SA) provides a much higher flow rate at low work rates, whereas the demand controlled respirator (SE) gives higher flow rates at high activity levels.

The dynamic air flow pattern of a breath cycle varies between the types of respirators. Of interest for the evaluation of protection is among others the flow rate over filters and face mask and the volume of air that travels at different flow rates. For passive filter respirators higher flow rates are likely to increase the negative pressure in the mask and thereby the risk of inward leakage. For all kind of filter respirators higher flow rates over the filter increase the risk of particle and gas penetration (Lathrache and Fissan, 1986; Lee and Liu, 1982; Linders et al., 2003), eventually reducing the protection factor.

In this study, constant inhalation flow rates in excess of 200 l/min and PIFR up to 600 l/min were measured. A flow rate of 95 l/min has been selected for standard filter testing (EN-143, 2000). This may not be sufficient to ensure required protection factors. This flow rate should be reconsidered in light of the high flow rates that can be achieved, in particular with power assisted respirators.

The health risk for the wearer depends on the amount of the agent that reaches the lungs. If the high flow rate only persists for a fraction of a second, the associated, inspired volume may be small and the risk increase negligible. If time is longer and volumes are larger, the risk may increase.

For the negative pressure respirator (SP) inhalation time varies from about 20% up to about 75% of the breath at high work rates. With speech it is about 75% at all work rates.

$V_E$ is by definition calculated for a whole breath cycle. The same volume is inhaled for a fraction of the breath cycle and exhaled during the remaining time. This implies, immediately, that inspiratory flow rates become higher than $V_E$ when inhalation time is shortened, in particular during speech. Table 2 shows the values for the highest work rate that all eight subjects completed. Mean inspiratory flow rates are 1.2–2.2 times higher than $V_E$ or about 200 l/min or more. This mean flow rate is more than 2 times higher than the standard test flow rate of 95 l/min.

At work rates requiring an oxygen uptake of about 2 l/min or more, the PIFR is higher than 95 l/min for 50% or more of the total inhalation time, irrespective of respirator type. This means that a person performing work with a minute ventilation of 60 l/min inhales at least 30 of these liters at a flow rate much higher than 95 l/min. With one of the respirators (SA) all 60 l are inhaled at a flow rate of about 200 l/min.

As mentioned, filters are tested at a constant flow rate of 95 l/min. This means that the performance of filters at substantially higher flow rates is not known. This has consequences for the assessment of protection factors in a real user situation. Janssen et al., (Janssen et al., 2005) concluded that the best available information for the moment, did not justify testing at higher flow rates. They stated that there appears to be a sufficient margin of safety already built into respirator approval tests. As already mentioned, however, the risk of impaired filtration efficiency, shorter break through times and reduced capacity at high flow rates justify a reconsideration of test flow rates. More studies should focus on performance of filter respirators, in particular power assisted respirators, that are supposed to be used at high work rates.

CONCLUSIONS

High work rates can be sustained for several minutes with modern types of filter respirators, at least when particle filters are used, as well as with power assisted filter respirators. Minute volumes may exceed 100 l/min providing mean inhalation flow rates of 200 l/min or more. This is associated with instantaneous flow rates in the mask that exceeds 300–400 l/min (~5–7 l/s). During speech the flow rate is further increased. Such high flow rates suggest that filters be tested at higher flow rates than are required in today standards.

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REFERENCES


