Over Breathing a Loose-Fitting PAPR

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ABSTRACT

Loose fitting powered air purifying respirators (PAPRs) utilize a motorized fan to draw air through the respirator's air purifying elements, delivering clean air to the wearer through a face piece that does not form an airtight seal with the wearer's face. Potential for wearer exposure to contaminants may exist if the breathing rate of the wearer exceeds the airflow rate supplied by the PAPR fan. In such an instance, ambient air could bypass the filters and enter the mask, potentially exposing the wearer to contamination. This investigation assessed the extent to which over breathing occurred in the Centurion MAX loose fitting PAPR. Sixteen subjects exercised at 80-85% $\dot{V}O_2 \max$ on a treadmill while wearing the PAPR inside a Portable Breathing Chamber (PBC). All subjects inhaled more air than was supplied by the PAPR blower, and 17% of the breathing volumes exceeded the 1.4 L dead volume of the PAPR face piece.

Keywords: respiration, flow rates, exercise, dead volume

INTRODUCTION

Powered air purifying respirators (PAPRs) are respirators equipped with a blower and battery pack assembly that draw ambient air through the respirator filters and deliver it to the wearer via the facepiece. The PAPR design is intended to supply clean, breathable air to the wearer without relying on the inhalation of the wearer, thereby decreasing respiratory fatigue and increasing wearer comfort. Various types of facepieces are compatible with PAPRs, including half and full tight-fitting facepieces, as well as loose fitting hoods and helmets.

A significant benefit offered by both tight and loose fitting PAPRs is the reduction in inhalation resistance that the wearer experiences during tasks requiring work at 80-85% of their maximal oxygen consumption. During tasks occurring in this range, the wearer is most sensitive to respiratory stress (Johnson and Cummings, 1975). Performance time at this work rate has been found to decrease linearly with increasing filter resistance (Johnson et al., 1999). A PAPR could therefore improve performance time by decreasing the amount of inhalation resistance experienced by the wearer.

Loose fitting PAPRs offer certain additional benefits to the wearer, including compatibility with facial hair and various facial structures. They may induce less feelings of claustrophobia in wearers, and they can be over breathed without additional effort. In the case of helmet-style PAPRs, cranial protection is an additional benefit to the wearer that may be useful for tasks that carry the risk of head injury, as in mining or construction.

Most PAPR blowers supply a relatively constant airflow rate regardless of the breathing rate of the wearer. At fairly light work rates the wearer's breathing rate is likely to be less than the airflow rate supplied by the PAPR blower. However, at higher work rates the breathing rate may meet or exceed this airflow rate. When the wearer's breathing rate exceeds the blower airflow rate, over breathing of the PAPR blower occurs. In a tight fitting PAPR the wearer over breathes by drawing air through the filters using his/her own inhalation effort. In a loose fitting PAPR, ambient air may bypass the filters and enter the mask directly through spaces between the wearer's skin and the facepiece, increasing wearer exposure to contaminants.

Preliminary testing in our laboratory indicates that for exercise occurring at 80-85% of the wearers' maximal oxygen consumption, instantaneous breathing flow rates in excess of 400 L/min may be observed, even if average air flow rates remain low (unpublished data). As many PAPR design specifications only incorporate fan airflow rates in the range of 120 L/min, over breathing may be a significant concern at these work rates.

Understanding the physiological compatibility of a wearer with loose fitting PAPR components (like blower speeds) becomes particularly important for wearers working at unpredictable rates. Workers in mining, construction, emergency rescue, and agriculture, among others, may be required to perform tasks at high work rates that elicit over breathing. Exposure to contaminants may therefore become a risk for these individuals (OSHA, 2001).

The Occupational Safety and Health Administration (OSHA) has established regulatory guidelines for exposure to certain contaminants in the workplace. These permissible exposure limits (PELS) are based on input from physiological data, laboratory testing, and industry concerns, among other factors, and are given either as time weighted averages (TWAs) for an eight-hour workday or as ceiling values. Tables for individual contaminants are given in the Code of Federal Regulations (OSHA, 2001) under 29 CFR 1910.1000s subpart Z, tables z1, z2, and z3. Similarly, the American Conference of Governmental Industrial Hygienists (ACGIH) has established recommendations for threshold limit values (TLVs) to be used as guidelines in industry for exposure to hazards (ACGIH, 2004). However, these values are not legal standards. The permissible respirable dose of a contaminant may be identified from either a PEL or a TLV by assuming a breathing flow rate if the ambient concentration of a contaminant is also known.

Over breathing of a loose fitting PAPR would result in some measurable volume of ambient air entering the breathing vicinity of the wearer. The wearer's dose of contaminant depends, therefore, on his/her breathing rate in excess of the airflow supplied by the PAPR fan, the contaminant concentration, and the duration of exposure. The purpose of this study, then, was to measure over breathing in one type of loose fitting PAPR.

METHODS

Sixteen subjects were recruited to participate in this study from the University of Maryland, College Park student body. The study was approved by the University of Maryland Institutional Review Board, and all subjects gave their informed consent to participate. Subjects completed a medical history questionnaire prior to testing that was used to ascertain general health information, as well as to screen for individuals with cardiovascular or respiratory disease, as these conditions would preclude their safe participation in the study. All subjects were categorized as non-anxious by the Spielburger State-Trait Anxiety Inventory (STAI), which was administered prior to testing (Spielburger et al., 1970). Subject statistics are given in Table I.

$\dot{V}O_2$ max Pre-Test

Prior to the start of the experiment, a maximal oxygen consumption test ($\dot{V}O_2$ *max* test) was performed on each subject using a Quinton (Bothell, WA) motorized treadmill and a modified Bruce incremental treadmill exercise protocol. Subjects were asked to warm-up and stretch for approximately 5-10 minutes prior to the start of the test, and were then equipped with a Hans Rudolph (Kansas City, MO) one-way breathing valve configured with a rubber adaptable mouthpiece. This apparatus was interfaced with a standard Fleisch (Phillips and Bird, Richmond, VA) pneumotach and Perkin Elmer (Pomona, CA) model 1100 mass spectrometer to monitor continuous expired airflow.

Table I. Subject Demographics (Values given are means ± standard deviations)

Age (y)	24.73 ± 5.66
Mass (kg)	67.61 ± 14.52
Height (cm)	168.40 ± 8.74
Maximal Oxygen Consumption (L/min)	2.66 ± 0.79
Maximal Heart Rate (bpm)	192.62 ± 9.13
Trait Anxiety Score	34.5 ± 9.69
Sex	8 males, 8 females

The initial work rate was established at a speed and grade designed to elicit 70% of the participant's age-predicted maximal heart rate. The work rate was adjusted by increasing the treadmill grade and speed every third minute until the participant experienced volitional fatigue, failed to display a rise in oxygen consumption rate of 150 mL O_2/min or more in accordance with the increase in work rate, or exhibited cardiovascular responses that contraindicated further assessment.

Sub-maximal oxygen consumption values (80-85% of each subject's $\dot{V}O_2$ *max*) and testing conditions (treadmill speed and grade) were obtained from this testing. Efforts were made for the subject to achieve the 80-85% $\dot{V}O_2$ *max* values at a treadmill speed and grade that would allow them to walk rather than run on the treadmill. These precautionary measures were taken in order to minimize unnecessary jostling of the testing apparatus, connecting hoses, and measurement devices.

Experimental Testing

Experimental testing commenced several days after the $\dot{V}O_2$ *max* test. Subjects wore the loose fitting Centurion MAX Powered Respiratory Helmet, E140ISEW USA (Martindale Protection, Norfolk, UK). A switch on the PAPR visor activated the blower when the visor was in the down position. The visor sometimes interfered with the Portable Breathing Chamber, PBC (described below), causing the blower to turn off during testing. To solve this problem, the power connection to the blower was modified to connect directly to a dc power supply maintained at a voltage corresponding to the measured full-charge battery voltage of 4.5v. During testing of this PAPR, it was found that the battery discharged at a rate too fast to allow multiple tests without recharging, and that this had a large effect on blower flow rate (Figure 1). Use of the dc power supply eliminated battery discharge as a consideration for our measurements.

Over the PAPR, subjects wore a portable breathing chamber (PBC) that was designed and constructed specifically for this investigation. The PBC was constructed from a large (39cm high x 39cm dia) polyethylene cylindrical food container (Figure 2). The container was used in the upside-down position, so that the top of the container (lid) was located at the subject's neck and the bottom of the inverted container rested above the PAPR helmet. The lid had a 23cm diameter circular hole and a slit from the edge to the hole, so that it could fit around the neck of the subject (Figure 3). A rectangular (14cm x 62cm) hole cut in front of the PBC was sealed with a visor of clear polycarbonate to allow the subject to see while walking on the treadmill. A piece of foam rubber in the PBC top cushioned the PAPR helmet from the PBC. The weight of the PBC was 1.9kg and the weight of the PBC and PAPR combination used in this study was 3.6kg.

The PBC body had two inlet/outlet ports installed. One port located near the nape of the wearer's neck allowed ambient air to reach the blower through a tube fabricated from a flexible heavyweight plastic material attached to the PAPR helmet blower intake port. The second port was designed to measure air exchange with the atmosphere that did not go through the blower and filter. Of particular interest was any indication of inhalation air through this port, because this was air required by the subjects over and above that supplied by the blower. This air was measured with a Fleish pneumotach connected to the PBC by a 1 m long piece of flexible tubing. Pressure across the pneumotach was measured with a Validyne (Northridge, CA) DP15 differential pressure transducer. Most measurements were made with a Fleisch #4 pneumotach (resistance = 0.067 $cmH_2O{\cdot}sec/L$); some were made with a Fleisch #3 pneumotach (resistance = 0.13 $cmH_2O{\cdot}sec/L$). One pneumotach or the other was chosen to: 1) assure linear response for flow rates estimated before testing began, 2) keep outlet/inlet resistance as low as possible, and 3) give maximum differential pressure signal. Flow measurements were calibrated before each test by discharging a 3L syringe through the pneumotach.

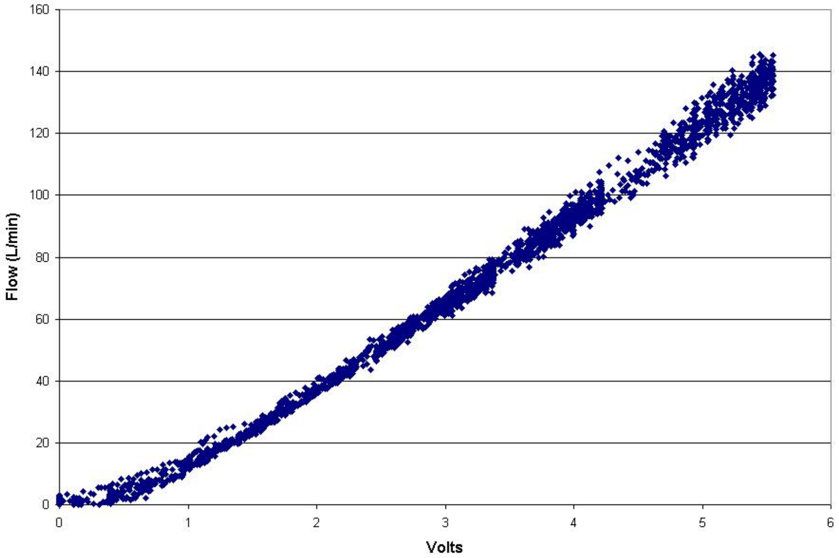


Figure 1. Battery voltage-flow rate characteristic of the Centurion MAX PAPR used in this study. Steady state flow rate was measured with a Fleisch #3 pneumotach in series with the blower and filter. At a battery voltage of 4.5v, steady state flow rate was 110 L/min.

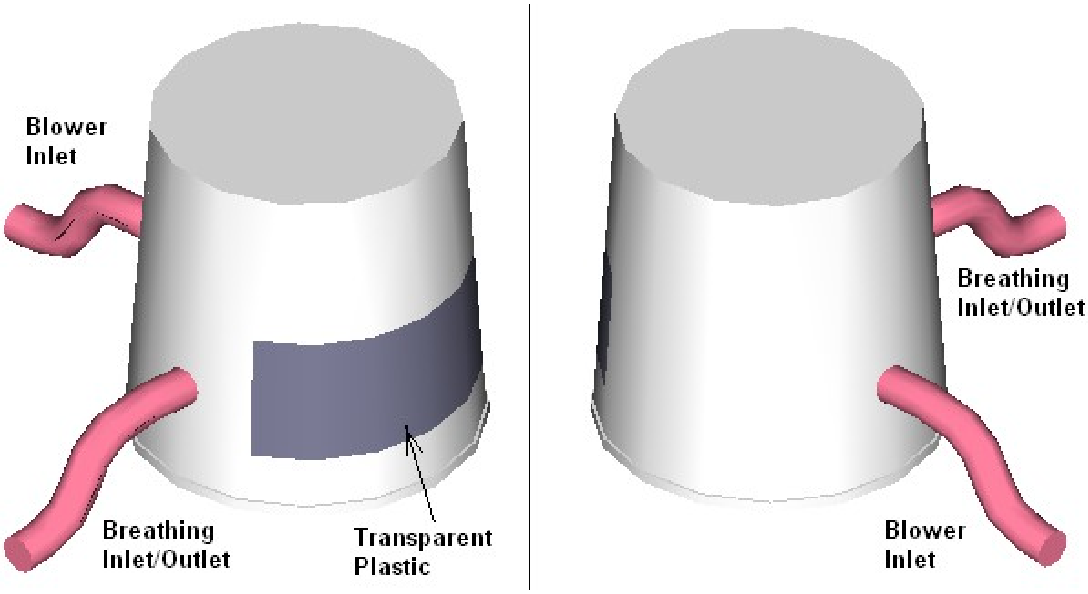


Figure 2. Diagram of the portable breathing chamber (PBC).

Figure 3. Photo of the PBC as worn. The subject's face can be seen through the visor.

The Fleisch pneumotach and Validyne pressure transducer were interfaced with a personal computer. Data were logged and recorded at 25 Hz using custom-designed software developed in Labview (National Instruments, Austin, TX) and Microsoft Excel specifically for this study. Each participant was asked to warm-up and stretch for approximately 5-10 minutes prior to the start of each test session. The subject then sat and was prepared for testing. Heart rate electrodes were applied, and the neck of the subject was encircled with a flexible plastic cylinder made from a thick, durable plastic bag with the bottom cut open. The circular opening in the PBC lid was adjusted around the subject's neck. The bag was taped to the neck with tightness similar to a necktie.

All hose connections and interfaces with the PBC were sealed to prevent leakage except the seal around the neck of the subject. To estimate the magnitude of possible leakage through the neck seal, the PAPR blower was disabled, and the blower inlet hose was connected to a Krug Life Sciences (Houston, TX) breathing machine. Pneumotachs were inserted in both the blower inlet hose and breathing inlet/outlet hose. The Fleisch #3 pneumotach in the blower inlet hose measured flow to and from the breathing machine, and the Fleisch #4 pneumotach in the breathing hose measured air flow taking that path. These two pneumotachs had been previously calibrated to make sure that they both measured the same flow rate when placed in series. The ratio of flows measured with both pneumotachs was 1.06. Neck seal leakage was determined as the ratio of flow rates at the two locations. This arrangement was tested with the PBC on a head form and also on six standing human subjects while holding their breaths. Results show that some leakage did occur. Leakage from the PBC on the head form was found to be 20% of the measured breathing machine flow rate. Leakages from the five subjects were found to be very consistent at about 52%. That is, flow measured at the breathing inlet/outlet port (Figure 2) was about 48% of the flow measured at the blower inlet port where the flow source was connected (measurement average and standard deviation were 0.48 ± 0.01 L/min, range was 0.45 – 0.51). It was concluded from this that flows measured at the inlet/outlet port were about half as large as the actual flows.

Both PBC and PAPR visors were treated with anti-fog spray. The PAPR was put on the subject and chin strap adjusted for comfort. The PAPR visor was pulled down to the operate position. The PBC was placed over the PAPR and both air connections made. The PBC bottom was sealed to the top, and an inspection was made for leaks. The dc power supply was connected and air began to flow.

Tests were conducted while subjects walked on a treadmill at 80-85% $\dot{V}O_2\,max$. Treadmill speed and grade were set initially to elicit 70% of the subject's age-predicted maximal heart rate. Speed and grade were slowly increased to predetermined values for 80-85% of $\dot{V}O_2\,max$. Each participant was asked to exercise at this intensity for 6 minutes. Air flow data of interest occurred during the last three minutes, after steady-state had been reached.

Over breathing this loose fitting PAPR would not be harmful to the wearer if contaminated air did not reach the mouth or lungs of the wearer (exactly where harm would come depends largely on the type of contaminant, if and where it is deposited or absorbed, and its potency). If air is assumed to reach the mouth from all directions inside the visor, then the full dead volume of the visor in front of the face can be considered to be a margin of safety against over breathing. The dead volume of this PAPR was measured on a head form with all respirator cavities and the gaps between visor and head form taped shut. A known volume of dried lentils of known density was used to fill the visor dead volume. The weight of the lentils in the container after filling the dead volume was subtracted from the original weight of lentils in the container. The difference, when multiplied by lentil density, gave the face piece volume of the PAPR on the head form as 1.4 L. Measurement of face piece dead volume on live subjects with different facial configurations was not attempted.

RESULTS

Every data point for inhalation portions of breaths during the last three minutes of the tests was analyzed for the occurrences of various over breathing flow rate values. Faulty equipment calibration required that data from two subjects be discounted. These occurrences were classified into different ranges, and the percentages of flow rates that fell into each range were calculated for each subject. Results for different subjects differed considerably. All subjects exceeded PAPR fan capacity during their tests.

In Figure 4 are results averaged over all subjects. Graphed in the Figure are volumes inhaled per breath above the volume of air supplied by the blower (over breathed volumes) without correcting for PBC leakage. Actual volumes, corrected for leakage, would be twice as large. Volumes were categorized into ranges, with the percentage of breaths with volumes in each particular range given by the height of the bars. All subjects over breathed the PAPR; about 17% of breathing volumes exceeded the 1.4 L dead volume of the PAPR visor. Over breathing flow rate categories as an average for all subjects are given in Figure 5. All instantaneous corrected flow rates were above 38 L/min, 30% were above the 120-158 L/min range, and a small proportion (about 1%) of flows was in the 520 – 558 L/min range.

DISCUSSION

The Centurion MAX PAPR tested in this study has been used in the mining industry because of its ability to filter particulates in the size range of coal dust, the added cranial protection afforded by the built-in helmet, and the cooling effect of the PAPR blower. Results from this test demonstrate that wearers working at the high rate used in this test regularly over breathe this loose fitting PAPR. Several subjects inhaled volumes greater than the measured dead volume of the PAPR, and so would be at risk for contaminant exposure.

The TLV (ACGIH, 2004) for coal dust is 2ppm, or 2mg/m^3. If the ambient concentration of respirable coal dust is 2 mg/m^3 or less, then the TLV requirement is satisfied regardless of whether respiratory protection is used or not. Hence, over breathing of a loose-fitting PAPR in this ambient dust concentration will not result in a condition outside recommended limits. At least in this respect, our results indicate that the performance of this PAPR is automatically acceptable under conditions of low contamination.

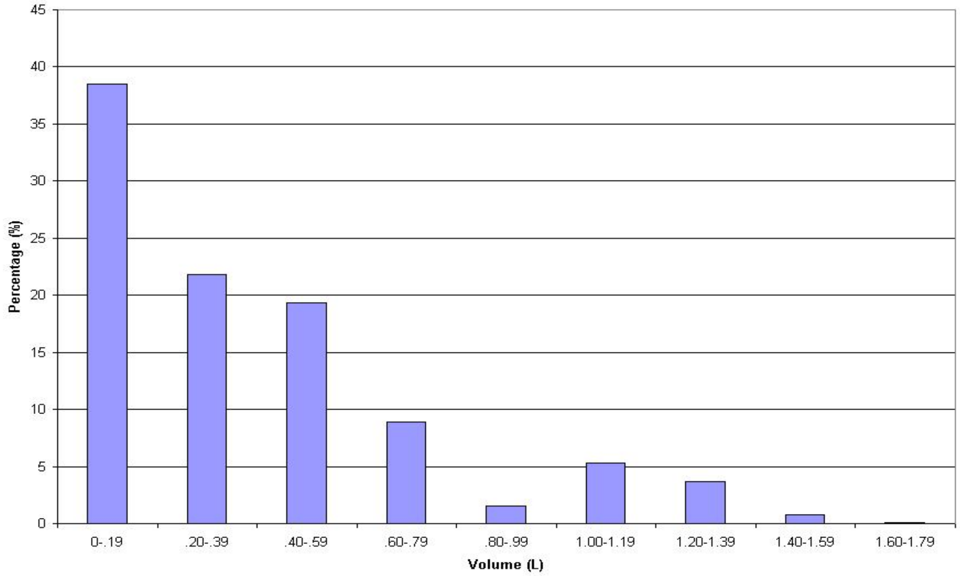


Figure 4. Over breathing inhalation volumes averaged for all subjects. Percentages of breaths with volumes in each category are shown on the vertical axis. Correcting for PBC leakage would give volumes twice as large.

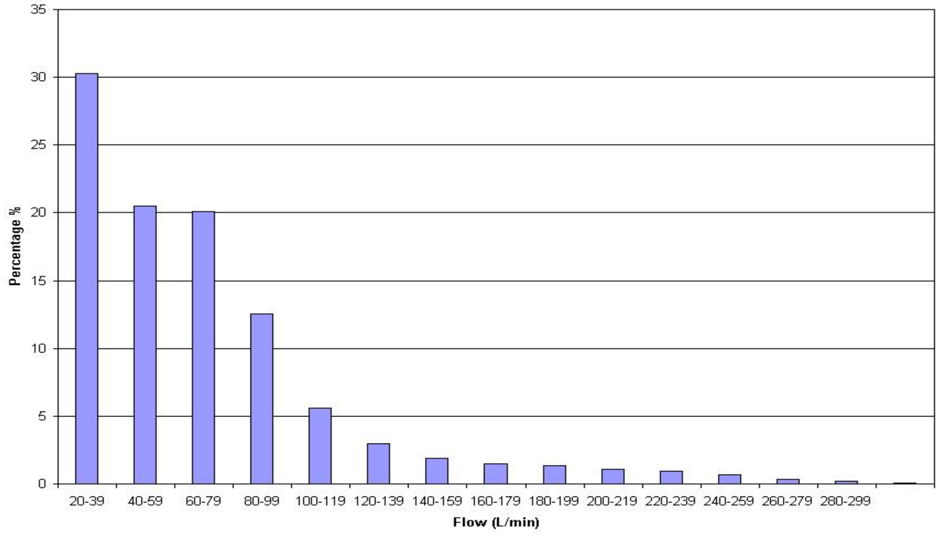


Figure 5. Flow rate ranges for the occurrence of over breathing. Values given are the average for all subjects. Correcting for PBC leakage gives flow rates twice as large.

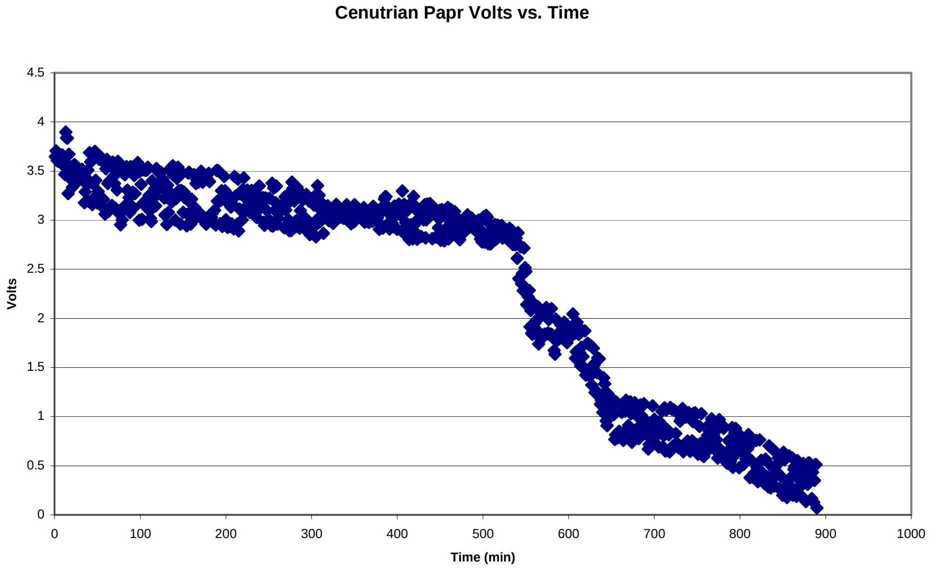
It is likely, however, that mine dust samples do not represent the extremes that could be reached near the face of the seam or near coal-handling equipment. Thus, there is concern that the respirator provides sufficient protection of worker health even under these conditions.

Bostock (1985) investigated the inward leakage of aerosols into a loose-fitting PAPR incorporating a hood or a blouse. The hood or blouse provided a pathway through which exhaled air and excess blower-supplied air could escape to the outside. The hood or blouse also contributed a large dead volume that acted as a buffer against inward leakage of ambient aerosol. His measurements showed that even when peak inspiratory flow rate exceeded the blower flow rate, the concentration of aerosol within the PAPR remained below 0.1% of the ambient concentration.

Although our study did not include leakage measurements, the Centurion MAX did use a blouse at the sides of the face shield. Hence, it likely acted similarly to the devices tested by Bostock (1985). That is not to say that the Centurion MAX provides an absolutely safe environment around the face of the wearer, but, given that it is voluntarily used in coal mines with engineering controls in place, and dust levels are controlled by water sprays and air ventilation to the presumed safe PEL, over breathing of the PAPR fan does not likely lead to dire consequences under these circumstances.

Bostock (1985) did, however, measure elevated levels of carbon dioxide inside the devices he tested. The same dead volume that protects against breathing ambient levels of aerosol also accumulates exhaled CO_2. We did not measure CO_2 levels in our tests, but it is reasonable to expect CO_2 concentration was high. If so, it is also likely that the elevated CO_2 stimulated breathing and contributed to over breathing of the blower. Confirmation of leakage and CO_2 accumulation will have to await further testing.

We found in our testing that the blower battery voltage degraded relatively rapidly (Figure 6). If we had not used a dc power supply, over breathing inhalation volumes would likely have been higher. The blower in this particular PAPR does not seem to be very powerful, so the use of the Fleisch #4 pneumotach, with a low resistance of 0.067 cm $H_2O \cdot \mathrm{sec/L}$ (a very low resistance, approximately 2.5% of the standard resistance of a U.S. Army M17 air purifying respirator filter), was necessary if flow rate delivery was not to be changed by the flow rate measurement. Over breathing of this PAPR could be minimized if both blower and battery were improved. According to the data in Figure 5, the blower flow rate could increase by about 400 L/min to eliminate all over breathing.



Battery Characteristic of Loose Fitting PAPR

Figure 6. PAPR battery voltage with time during use. Battery voltage decreased very rapidly, especially after 500 min.

The visor switch controlling blower operation was extremely sensitive. If the visor hit the chest or shoulder of the wearer, the blower was sometimes found to turn off . In a high noise environment it was not always possible to hear whether the blower was operating. No other blower operation indicator was provided, and it was so easy to breathe air circumventing the blower and filter that breathing contaminated air would often be undetectable. For the same reason, different hair styles may obstruct either the blower inlet or outlet, and this would be hard to detect.

It should be noted that there is a large difference in blower flow rates between our results reported here (110 L/min at 4.5v) and test results supplied by the manufacturer (205 L/min at 4.8 v). There are several possible explanations for this large discrepancy, including faulty batteries (not likely because most of our testing used a dc power supply in place of the battery), one of the two blower fans was inoperative (not likely, since operation of both fans was checked before each test), or the addition of extra pneumotach and hose resistance in the air flow circuit (this is possibly the reason). Devices were tested by the manufacturer using the European standard EN 146/EN 12941. Flow rate is determined by a zero pressure difference method: flow is introduced into a chamber by the device under test, and flow rate out is produced by a blower independently controlled to match the flow rate of the blower under test. When the pressure in the chamber equals the pressure outside the chamber, then flow rates from both blowers are matched. So, the additional pneumotach and tubing resistance could have contributed to the smaller flow rates we measured compared to the manufacturer's data, although it is hard to believe that some small resistance could have decreased flow by this amount. Even slight crimping of the blower inlet tube that could have occurred during human testing did not occur during head form testing when the data appearing in Figure 1 were obtained.

Because of the large discrepancy between measured and specified flow rates, our methods were checked and rechecked. No other connections or modifications were found to hinder blower operation as it is situated inside the PAPR.

Despite the difference in method and results, what are the likely consequences of added resistance in the blower circuit? The resistance of our flow-measuring instruments was very small. It is possible that a wearer's hair or a filter clogged with dust could provide at least as much resistance as our measuring devices, so it is possible that flow rates could be severely reduced.

At this point, the path of over breathed air into the face piece is not known, and must be determined by subsequent investigation. If there is a preferential direction for outside air to enter the face piece, then the entire 1.4 L face piece volume would not be protective. There seem to be differing opinions about whether the entire face piece volume must be breathed before contamination reaches the mouth, but no scientific study reports have been found to illuminate this issue. It is possible that the cloth barrier to be worn around the face when using the PAPR could be counter-productive by directing air through specific pathways rather than allowing the air to come in from all directions. Only further testing will tell.

CONCLUSIONS

All subjects exercising at 80-85% $\dot{V}O_2$ *max* intense exercise rate over breathed the PAPR to some extent. Over breathing could potentially expose the wearer to contaminant risks.

ACKNOWLEDGEMENT

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