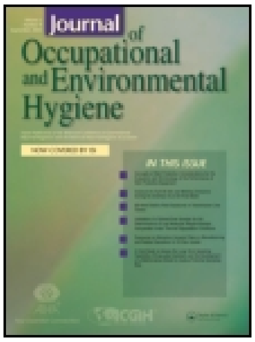

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Human Subject Testing of Leakage in a Loose-Fitting PAPR

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Leakage from loose-fitting PAPRs (powered air-purifying respirators) can compromise the safety of wearers. The Martindale Centurion MAX multifunction PAPR is a loose-fitting PAPR that also incorporates head, eye, and ear protection. This respirator is used in mines where coal dust usually is controlled by ventilation systems. Should the respirator be depended on for significant respiratory protection? Ten human volunteers were asked to wear the Centurion MAX inside a fog-filled chamber. Their inhalation flow rates were measured with small pitot-tube flowmeters held inside their mouths. They were video imaged while they breathed deeply, and the points at which the fog reached their mouths were determined. Results showed that an average of 1.1 L could be inhaled before contaminated air reached the mouth. As long as the blower purges contamination from inside the face piece during exhalation, the 1.1 L acts as a buffer against contaminants leaked due to overbreathing of blower flow rate.

Keywords dead volume, protection, protection factor, respirator

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INTRODUCTION

Loose-fitting powered air-purifying respirators (PAPRs) have the advantages that they never restrict breathing of the wearer, and they can accommodate items, such as normal eyeglasses, worn on the face. Air drawn by a blower through a filter is blown across the face and intersects the normal path for breathed air to enter the mouth. Thus, under quiet circumstances, the air that is inhaled should be filtered air. When exertion increases and breaths become deeper, however, there is little to impede contaminated air from mixing with the filtered air. Most loose-fitting PAPRs incorporate a face shield, and some have a cloth scarf spanning the gap between the face shield and face or neck to impede contaminated air from entering the vicinity of the mouth.

Mackey et al.(1) published a report about overbreathing a multifunction, loose-fitting PAPR, the Centurion MAX (Martindale Protection, Thetford, Norfolk, U.K.). They reported that all 16 subjects inhaled more air than was supplied by the PAPR blower. In the same paper they also reported a measured volume inside the face shield of 1.4 L. They contended that if the whole 1.4 L was protective, then the problem of overbreathing would be minimal. This condition would have required diffuse, nonpreferential flow of outside air into the facepiece.

Experiments have been conducted on a loose-fitting PAPR mounted on a head form and challenged with generated fog. (Unpublished observations) The breathing machine was adjusted such that inhaled flow rate exceeded blower flow rate. It was found that the volume of air inhaled before fog reached the mouth averaged 1.4 L. The present experiment was conducted to determine whether the same results can be anticipated for human wearers. If so, then the volume inside the facepiece could be considered to be protective dead volume that buffers against inhalation of airborne contaminants while overbreathing the PAPR blower.

METHODS

Ten young, healthy (determined by questionnaire) participants volunteered from the University of Maryland student body, and each signed a consent form before participating. This protocol was approved by the University of Maryland Institutional Review Board.

Subjects sat in a full body chamber constructed of plywood and could be observed through Lexan plastic windows. Overall dimensions of the chamber were 137 cm long by 76 cm wide by 180 cm high. The rigid plastic window at the front of the chamber was replaced by a transparent, thin plastic film normally used to reduce home window drafts. Each subject wore a Centurion MAX multifunctional PAPR and leaned into the transparent film with the PAPR visor in contact with the film. Thus, it could be seen when fog that filled the chamber entered the space between the visor and the face.

Glycerol fog was produced outside the chamber with a Fog Storm (American DJ, Los Angeles, Calif.) 1200HD generator and introduced into the chamber through a hose inserted into a port in the chamber wall. The fog generator was capable of producing about 200 m^3 (7000 ft^3) of fog per minute. Fog filled the chamber in a very short time and was used as a safe and visible surrogate for contaminated air.

The aim of this research was to determine the amount of protective dead volume in the region between the face shield and the face. Hence, subjects were asked to inhale very deeply to induce fog to reach the mouth from the outside. To solicit a maximal inhalation and to allow dissipation of condensation that formed on the visor from the previous exhalation, each individual was instructed to exhale as completely as possible and to hold his/her breath for 15 sec before inhaling as deeply and quickly as possible. Filtered air from the PAPR blower was clear of fog and filled the visor space completely until the subject drew enough air from outside the facepiece by overbreathing the blower capacity. When that happened, fog could be seen entering the space behind the visor.

To improve fog visibility, each subject applied black face paint on their skin below the nostril, below the cheek line, and above the jaw line. A wire with two light-emitting diodes (LEDs) was draped over the ear and taped with black electrical tape near the lips to assist with video interpretation. One LED blinked at 10 Hz, and the other was driven by a comparator circuit working from the mouth flowmeter signal and indicated when the inhalation phase of breathing was in progress.

Measurement of flow rates was made with two MedGraphics (St. Paul, Minn.) pitot tube flowmeters. One was used to measure PAPR blower flow rate and was taped and sealed to the blower inlet with a flexible plastic cone. The other was cleaned and placed inside the subject's mouth with lips sealed around the pneumotach and associated tubing. Subjects wore nose clips to obstruct nasal flow. In this way, overbreathing could be detected as the difference between mouth and blower flow rates.

Calibration of the pneumotachs was extremely important because flow rate differences were to be calculated. The MedGraphics flowmeters were calibrated against a Fleisch #3 pneumotach (Phipps and Bird, Richmond, Va.) and then against each other by placing them in series and connecting them to a breathing machine. Flow signals were integrated to obtain volume, and this volume compared with syringe volume.

The Centurion MAX consisted of a helmet with a blower and particulate filter. Pivoted visor eye protection and ear muff hearing protection were attached to the helmet. A scarf was worn below the chin and around the mandible just below the ears. All components of the Centurion MAX PAPR were worn by the subjects as the manufacturer had intended. The visor was preheated with a blow dryer before being put on by the subject to reduce condensation from the exhaled breath.

Video images of the fog flowing inside the PAPR were recorded digitally with a Sony (Tokyo, Japan) DCR-HC90 camera with 3-megapixel resolution. The camera was aimed through the plastic film and face shield visor of the PAPR and focused on the area of the mouth. The experiment was conducted in a darkened room with two incandescent lights aimed toward the face from outside the chamber. Proper positioning of the lights eliminated glare from the visor and face.

Each image was frozen on the computer monitor using a program called Adobe (San Jose, Calif.) Premiere Pro 1.5. Pulsing of the LEDs helped to determine timing and respiratory cycle phase. Fog was determined to have reached the mouth when fog was observed at the edge of the mouth flowmeter. In actuality, there was very little time difference between the fog reaching the lips and when it was observed to have reached the flowmeter. All of these determinations were made very carefully and consistently by a single observer. Overbreathing flow rate (the difference between blower flow and mouth flow rates) was integrated from the moment that mouth flow rate exceeded blower flow rate until the fog was observed to reach the mouth. This gave the volume of filtered air that could be inhaled before outside contamination began to be inhaled. This determination was made for three breaths and the average calculated.

RESULTS

Figure 1 presents the comparative calibration of the two pneumotachographs used, showing that they matched extremely well and were statistically indistinguishable. Thus, flow rate differences determined from the two flowmeters could be calculated with confidence. Each flowmeter had a quadratic pressure-flow characteristic that was linearized mathematically before flow differences or flow integration was performed (Figure 2).

Figure 3 is a typical image showing the physical arrangement of the flowmeter and the path of the fog across the face and inside the face shield. In general, there were no significant differences between flow pathways seen with the breathing machine or the human face. The three-dimensional curling and twisting path taken by the fog as it entered the facepiece, flowed to the visor and reversed toward the mouth was seen for both human face and machine headform. (Unpublished observations)

Results of the human subject testing are summarized in the table. Average volume inhaled before contaminants (fog) reached their mouths (designated here as Total Prior Volume) was 1.11 L. For tidal volumes less than this value, airborne contaminants leaking in from around the periphery of this respirator would not be inhaled by an average wearer. Also given are standard deviations and ranges of the data. The range of individual breaths was 0.82 to 1.47 L before fog reached the mouth. Although this range is wide, the standard deviations for all subjects were mostly within 10% of individual means.

The Net Prior Volume is the Total Prior Volume inhaled by the subject subtracting the volume of air supplied by the blower from the beginning of the inhalation up to the point where fog reached the mouth. This assumes that all blower flow is inhaled and none short-circuits to the outside while the wearer is inhaling. The average Net Prior Volume was 0.66 L.

The Net Post volume is the volume of air inhaled that contains contaminants. It is the volume inhaled after fog reached the mouth and less the volume supplied by the blower

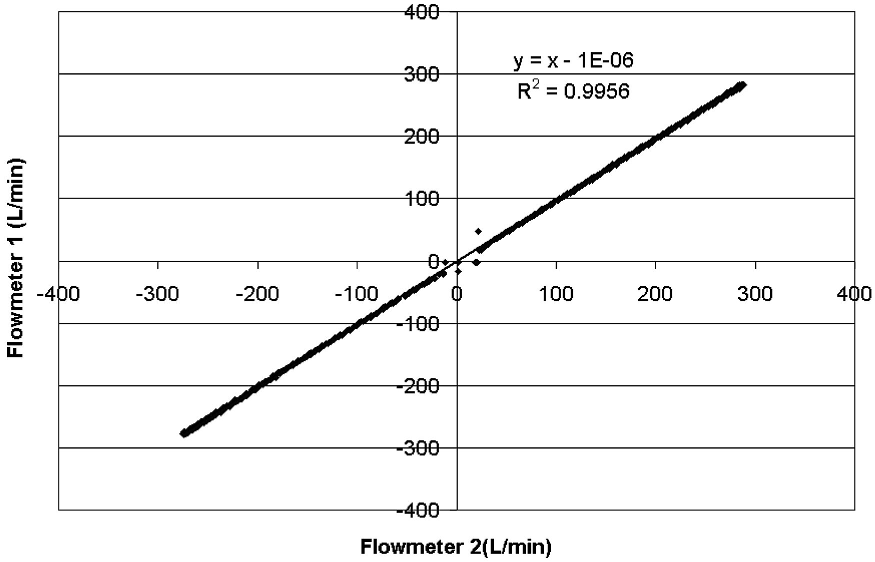

FIGURE 1. Comparison of calibrations between two flowmeters, showing that their outputs are nearly identical

at the same time, again assuming all blower volume is inhaled. The average value for Net Post Volume was 1.22 L, but this value would be expected to vary widely among individuals depending on the depth of breathing.

DISCUSSION

Being able to see the path taken by flow inside a PAPR facepiece can help to understand flow dynamics of the protective device. Visualization is needed to substantiate results from computational fluid dynamics computer programs and, perhaps, to improve protection of these devices.

The flow patterns proved to be complex, with twists and curls of a multiplanar nature. This twisting and curling has at least one positive and one negative effect. On the negative side, changing the magnitude and direction of a mass of fluid air required energy, so that the work required of the respiratory muscles during overbreathing of the PAPR blower is greater than it would have had to be had the flow pathway been simpler and straighter. Because the mass of air is very low, however, this extra work is usually insignificant.

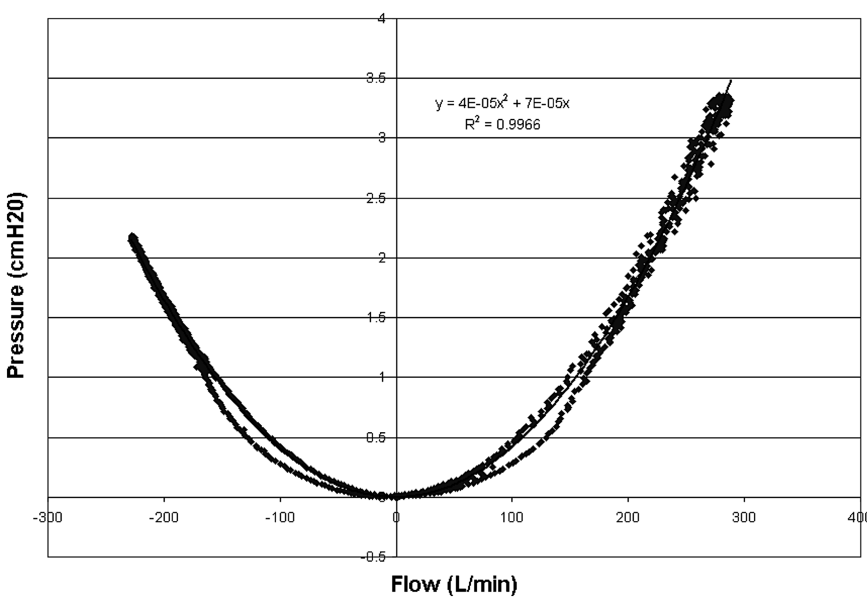

FIGURE 2. Quadratic calibration response of the Medgraphics pitot tube flowmeter. The flowmeter output was linearized mathematically.

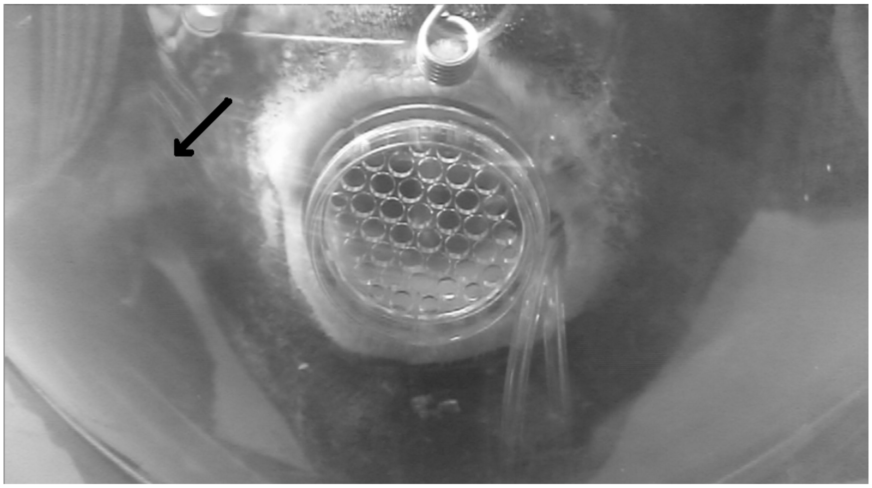

FIGURE 3. Typical facial image showing the mouth and pneumotach. The face was covered with black face paint to enhance fog visibility. The Medgraphics pneumotach appears in the mouth and is situated almost entirely within the oral cavity. Pressure tubes attached to the pneumotach can be seen on the right side of the pneumotach. Above the mouth is a spring belonging to a nose clip. Fog is slightly visible in this view (at arrow) as it reaches the mouth of the deeply inhaling subject.

On the positive side, the twisting and curling of the air entering the facepiece periphery effectively lengthens the flow pathway and increases the amount of "dead" air that can be inhaled before contaminated air reaches the mouth. Thus, effective dead volume of this respirator is increased by the complexity of the pathway. One goal of respirator designers then might be to cause contaminated air to curl in a vortex pattern before it reached the mouth, thus lengthening the flow path manyfold. This may provide more efficient protection than would increasing the blower or battery capacity. In the limit, it might be possible to provide as much wearer protection for a wearer of a loose-fitting respirator without a blower as loose-fitting devices presently with a blower.

So, why might a blower be needed at all? The answer lies in the nature of the air in the dead volume. The flow pathway for exhaled air is different from the flow pathway for inhaled air. Therefore, the dead volume fills with CO_2-rich and O_2-poor air during exhalation. This is the air that is first inhaled during the subsequent breath. If the effective inhaled flow pathway is lengthened too much, then it is only this air that is inhaled. The air would not be contaminated, but it would not be fresh.

TABLE I. Human Subjects Results

Subject Number	Total Prior Volume (L)	Net Prior Volume (L)	Net Post Volume (L)	Average Tidal Volume (L)
501	0.97 ± 0.04 (0.93–1.02)	0.42 ± 0.02 (0.40–0.45)	1.16 ± 0.11 (1.06–1.27)	2.25 ± 0.10 (2.16–2.37)
502	1.16 ± 0.08 (1.06–1.22)	0.74 ± 0.06 (0.67–0.79)	1.66 ± 0.10 (1.56–1.75)	2.66 ± 0.04 (2.63–2.71)
503	0.99 ± 0.11 (0.90–1.11)	0.60 ± 0.09 (0.51–0.68)	1.54 ± 0.08 (1.49–1.63)	2.59 ± 0.12 (2.46–2.69)
505	1.21 ± 0.05 (1.18–1.27)	0.76 ± 0.02 (0.74–0.78)	1.53 ± 0.64 (0.80–2.02)	2.41 ± 0.97 (1.31–3.16)
507	1.24 ± 0.04 (1.20–1.28)	0.79 ± 0.13 (0.66–0.92)	1.65 ± 0.12 (1.55–1.77)	2.67 ± 0.12 (2.48–2.70)
508	1.08 ± 0.24 (0.82–1.27)	0.71 ± 0.20 (0.49–0.86)	0.94 ± 0.19 (0.73–1.11)	1.70 ± 0.22 (1.50–1.94)
509	0.84 ± 0.01 (0.83–0.86)	0.32 ± 0.04 (0.28–0.35)	0.32 ± 0.04 (0.28–0.36)	1.00 ± 0.03 (0.98–1.04)
510	1.26 ± 0.14 (1.11–1.39)	0.90 ± 0.12 (0.77–1.01)	1.33 ± 0.21 (1.09–1.4)	1.90 ± 0.23 (1.63–2.07)
511	1.25 ± 0.19 (1.09–1.47)	0.77 ± 0.18 (0.58–0.95)	1.42 ± 0.32 (1.06–1.65)	2.80 ± 0.21 (2.55–2.96)
512	1.11 ± 0.16 (0.95–1.27)	0.57 ± 0.09 (0.47–0.62)	0.67 ± 0.09 (0.57–0.73)	1.40 ± 0.16 (1.25–1.56)
Avg	1.11 ± 0.14 (0.84–1.26)	0.66 ± 0.18 (0.32–0.90)	1.22 ± 0.45 (0.32–1.66)	2.12 ± 0.57 (1.00–2.80)

Notes: Volumes given are averages of three breaths. Also given are standard deviations and range of values. Subject Number refers to the number assigned in our laboratory. Total Prior Volume is the total volume inhaled by the subject before the fog reached the mouth. Net Prior Volume is the difference between subject inhalation volume and volume delivered by the blower before the fog reached the mouth. Net Post Volume is the difference in volume inhaled by the subject and supplied by the blower after the fog reached the mouth. Net Post Volume = [Subject Inhalation Volume After Fog Reached Mouth] – [Volume Delivered by the Blower After Fog Reached Mouth]. These terms were developed by the authors and are not in general use in industrial hygiene or respiratory protection fields.

It is the function of the blower to purge exhaled air from the dead volume during the exhalation portion of the breathing cycle. Filling the dead volume with fresh filtered air is all the blower needs to do. It does not need to supply inhaled air as long as the inhaled flow pathway is long enough.

This almost inverts the traditional concept of dead volume as something undesirable. Dead volume in a PAPR such as this now becomes protective, and not burdensome. The more protective dead volume present, the more effective is a loose-fitting respirator. With enough protective dead volume, there is essentially no difference between a loose-fitting respirator and a tight-fitting respirator. Thus, it is seen that some loose-fitting hoods can give as much protection as if they were tight-fitting respirators.

Hoods, however, have taken an extensive approach toward providing protective dead volume. They are large and require proper wear. Just as filtering materials and membranes can be folded to fit a very large surface area into a small volume, it may be possible to design a respirator that fits a long flow pathway into a small volume. This would be an intensive approach and should trade technology for materials.

One challenge that would be faced if this strategy were to be implemented is how to prove the protection afforded. Sampling contaminants inside the facepiece would have to be very carefully done, or else measurements would be too high. Most of the volume inside a facepiece could conceivably contain unacceptably high contaminant concentrations. Yet, if contaminants never reached the mouth, then the respirator would have achieved its purpose. New approaches are called for.

Another challenge would be isolating sensitive tissues from contaminants. Thus far, there has been concern only for inhaled contamination, but if the contaminants can irritate or damage the eyes or the skin, then this approach is not likely to succeed. In this case, tight-fitting PAPRs, APRs, or SCBAs would be required. Hence, as is already known, the selection of an appropriate respirator depends on the conditions under which it is to be used.

A third challenge for this approach would be coping with blower failure. In this case, CO_2 accumulated in the dead volume would not be swept clear by the blower during the exhalation phase. More likely than sudden failure of the blower is that the batteries would discharge and reduce blower flow rate. This condition would not be too bad because blower flow rate necessary to sweep at least some of the accumulated CO_2 from the dead space does not need to be as high as the flow rate to supply peak inhalation flow rate, insofar as all blower flow remains inside the respirator space and does not short-circuit to the outside. If the blower was to stop precipitously, then the buildup of CO_2 would occur over a long enough time that the wearer could detect it and take remedial action.

The most valuable figure determined by this study is the Total Prior Volume because that is an estimate of protective dead volume. Koh et al. (Unpublished observations) measured this as 1.55 L with inhalation supplied by a breathing machine. Physical measurement of the dead volume of the same respirator mounted on a headform gave 1.4 L.[1] The same volume was measured as 1.11 L in the present study with human volunteers. The difference among these figures is not totally unexpected because facial configuration may have a substantial effect on flow pathways inside the facepiece, and some areas are truly "dead" volumes because no flow ever passes through them. The flow curling that was observed would have been formed somewhat haphazardly as long as this characteristic was not specifically designed into the facepiece. The other two volumes in the table depend on the assumption that blower flow is totally inhaled and does not leak to the outside during inhalation. The assumption needs to be checked, and it is the authors' guess that it is not totally correct. A study has been conducted using CO_2 gas as a contaminant to determine, with a different method, the Net Post Volume of contaminated air inhaled. (Unpublished observations)

The value of Net Post Volume measured in that study was 0.6 L for the same respirator tested with a breathing machine set to produce a tidal volume of 2.4 L. The value of the same volume in this study is 1.22 L with human subjects breathing with an average tidal volume of 2.1 L. As mentioned before, the Net Post Volume depends strongly on the depth of breathing, so different results are to be expected.

CONCLUSIONS

Twists and curls in the flow pathway were found to increase the distance for contaminated air to reach the mouth when leaking from outside the facepiece. Fostering this increased flow path might prove to be a design technique for future respirators. If so, contaminant sampling methods inside respirator facepieces may have to be modified.

ACKNOWLEDGMENT

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