

Flow Patterns in Loose-Fitting PAPRs Help Explain Low Protection Factors

Frank C. Koh and Arthur Johnson*

Biological Resources Engineering, University of Maryland, College Park, MD 20742 USA

* Corresponding author & E-mail: artjohns@umd.edu

ABSTRACT

Respiratory protection plays an important role in maintenance of wearer health and safety. Previous research has shown that the two loose-fitting PAPRs tested here have very low protection factors. These respirators do not offer the protection that they are supposed to, and the question is why they do not. This investigation was undertaken to determine if these low values could be explained by the flow pathways taken by contaminated air from the leakage points to the mouth. Two loose-fitting powered air-purifying respirators were challenged with a glycerol fog to determine flow pathways and amounts within the facepieces. Fog was drawn from the environment around the respirator by either a steady vacuum (to determine flow pathways) or a breathing machine (to determine inhaled amounts). Movement of the fog within the facepiece was captured by digital video and examined frame-by-frame. It was found that the loose-fitting PAPR without a scarf offered no protection against the fog (protection factor ≈ 1), whereas the PAPR with a scarf allowed up to 1.4 L of inhaled breath before the fog reached the mouth (protection factor > 1). Tilting the head affected the amount of protection given by the PAPR. It was concluded that the presence of the blower was no guarantee of protection and that this PAPR should be worn only in a situation not dangerous to life or health.

Keywords: PAPR, respirator, inward leakage, flow visualization, protection factor

INTRODUCTION

Respiratory protective masks play an important role in maintenance of wearer health and safety. When engineering controls fail or are impossible to implement, workers need to wear respirator masks to protect against airborne contaminants. Respirators are worn by industrial workers, pesticide applicators, home owners, first responders, health-care personnel, and many others. All depend on the respirators to be effective as possible in protecting against unhealthy contamination.

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 inhaled air is expected to be filtered air. The presence of the blower is expected to offer at least a modest amount of protection to the wearer.

Nevertheless, Johnson et al (2011) measured wearer protection factors in several types of respirators, including loose-fitting PAPRs using a breathing machine. They used CO₂ as a challenge gas

that could only enter the facepiece through leakage sites, and collected breathing machine exhaled CO₂. Because there was no other pathway for CO₂ removal, the volume of exhaled CO₂ was equal to the volume of CO₂ inhaled by the machine. They determined that the wearer protection factor for a Racal AirMate 3 loose-fitting PAPR was 1.2, and was 4 for the Centurion MAX PAPR. These low values demonstrated that each of these loose-fitting PAPRs provided almost no protection for the wearer against airborne contamination.

This result was surprising because the blower circuit for each PAPR was expected to supply filtered the air that the wearer would breathe. However, this was not observed for some reason, so the objective this study was to investigate, by visualizing flow patterns within the PAPR facepieces, why the protection afforded by these two PAPRs is so low. The results of this study could give general insight into ways to avoid contamination exposure for wearers of respiratory protective masks.

METHODS

These tests were all conducted with the Centurion MAX (Martindale Protection; Thetford, Norfolk, UK) and Racal AirMate 3 (Racal, Frederick, MD, USA) respirators mounted on a medium-sized head form (Krug Life Sciences; Houston, TX). Both have transparent face shields with blowers supplying filtered air. The Centurion MAX also has a scarf that loosely fits around the periphery of the face shield and encloses the cheeks and chin. Visualization of flow pathways requires generation of visible fine particles and introducing them in the air outside the face piece. The paths taken by these particles must then be able to be seen as they cross the face enroute to the mouth. Fortunately, the face shields are transparent for the two PAPRs used in this study. The Racal Air-Mate 3 (Frederick, MD) loose-fitting PAPR is no longer commercially available, but differs from the Centurion MAX in that there is no scarf or ear muffs. Thus, a difference in the amount of unfiltered outside air entering the breathing zone, and the pathway taken by that air could be anticipated when comparing these two PAPRs.

Once the respirator was placed on the head form, it remained unmoved until all tests were completed. This eliminated the possibility that differences in respirator placement would affect results.

The head form was covered with black electric tape to increase visibility of the fog and not damage the original head form surface. A green light emitting diode (LED) was attached to the upper lip of the head form with the electrical wiring tucked under the black electric tape. This LED helped determine timing of the video frames during data analysis. A one inch long thin string/wick taped to the base of the bottom lip of the head form mouth fluttered in the direction of the breathing phase and helped identify inhalation or exhalation. The LED and string are shown in Figure 1.

Fog was introduced to the volume surrounding the respirator inside a portable breathing chamber (PBC) placed over the respirator and head form. The intention of the PBC was to contain the fog inside a relatively small volume so that flow pathways inside the PAPR could be observed, yet not bias positions of the leakage points or the amount of leakage that could enter beneath the PAPR face shield. Fog confined inside the PBC was not directed against the PAPR as it would have been if released from a nozzle or wand. The PBC has been described previously (Mackey et al, 2005), and consisted of a cylindrical plastic container with a rectangular transparent visor. In this case, the PBC visor was removed and the edges of the PBC were sealed to the respirator face shield with plastic wrap and transparent tape. This was done to prevent a layer of fog from forming between the PBC visor and the respirator face shield. Thus, any fog inside the PAPR face shield represented leakage from the edges of the visor. A 5 cm (2 inch) diameter opening at the top of the PBC and a gap around the neck at the bottom of the PBC were left open to allow outside air to be supplied to the respirator, avoid pressure build-up within the PBC, and allow free flow of exhaled air and blower output.

The Fogstorm 1200 HD (Los Angeles, CA) generates about 200 m³ (7000 ft³) per minute of fog. In order to minimize the momentum of the fog as it comes from the generator, which could influence the leakage airflow pathway, a fog retention container was created and placed between the generator and the PBC. A six gallon food grade bucket acted as storage for the fog and allowed a passive flow of fog into the PBC. The bucket lid was modified with two holes. Inserted through one hole (inlet) was a 2.5 cm (1 inch) inner diameter tube that reached the bottom of the bucket. This hose connected to the fog machine and supplied smoke to the bottom of the bucket. The second hole in the lid was the outlet with 1.3 cm (0.5 inch) inner diameter. Connected to the outlet hole was a 2.5 cm inner diameter tube that was inserted into the PBC next to the back of the head form. This allowed for an even distribution of fog throughout the PBC.

Two schemes of flow were used while the PAPRs were mounted on the head form. The first was steady inhalation flow caused when a vacuum line was connected to the flow pathway through the head form. This condition was used to ascertain the path taken by the fog into and inside the face piece, but does not represent actual use conditions. With the PAPR blower off, it was possible to determine points where the fog entered the face area. With the PAPR blower on, flow pathways inside the face piece could be seen. The vacuum-induced steady flow was kept greater than blower flow to determine flow pathways inside the face piece.

The second flow scheme consisted of sinusoidal breathing while the PAPR blower supplied air to the face area. This flow condition was used to determine the inhaled volume of air when the fog first reached the mouth. Blower flow rates were held constant. A dc power supply was set at 4.5v and ran the Centurion MAX blower at a nominal 100 L/min specified for the device. The battery terminals for the Racal AirMate 3 were not accessible, so the battery was fully charged and the blower supplied air at a measured 211 L/min. A Krug Life Sciences (Houston, TX) breathing machine was used to provide a controllable breathing air flow to the PAPR.

Flow rates were measured with Fleisch (Phipps & Bird; Richmond, VA) pneumotachs and Validyne (Cupertino, CA) DP-15 pressure transducers. A Fleisch #3 pneumotach was used to measure the flow at the mouth of the head form, and was located upstream from, and on the distal side of, the head form. A Fleisch #4 pneumotach was used to measure PAPR blower flow rate. It was located at the inlet side of the blower and attached to the blower with a plastic adapter between the pneumotach and the inlet filter of the Centurion MAX. The pneumotach was placed in the supply hose of the Racal Air Mate 3, on the discharge side of the blower. A computer program using LabView 4 (National Instruments; Austin, TX) logged flow rate data. The electrical signal lighting the LED was also logged concurrently.

After the PAPR was fitted on the head form, the PBC was placed over the ensemble. The scarf that came with the Centurion MAX was put into place correctly as recommended by the manufacturer: it was evenly centered, covering the gap between the face shield and chin, and had a small gap near the ear lobe and lower jaw line. It was loosely in contact with the head form beneath the chin. Fog was then introduced into the PBC. The Racal PAPR had no scarf.

Breathing machine minute volumes used were 31, 70, 89, 110, and 121 L/min. Respiration rates were held at 30 breaths/min for each minute volume. This would give tidal volumes of 1.5, 2.4, 3.0, 3.6, and 4.0 L for each condition.

It was suspected that head pitch (angle displacement up or down) and roll (angular displacement side to side) could affect preferential flow pathways. In order to test this supposition, the head form was tilted 5.9 degrees (pitch) and the side-to-side tilt (roll) was set at 4.8 degrees. Steady flow was used with the blower on to determine flow pathways inside the face piece. Pitch and roll measurements were made only with the Centurion MAX respirator.

Video images of the visualized flow inside the face piece were recorded digitally with a Sony (Tokyo, Japan) DCR-HC90 AVI-protocol camera with 3 megapixel resolution. The camera was aimed through the visor (face shield) of the respirator and focused on the area of the mouth. Two conventional desk lamps each with 75 watt incandescent bulbs were placed on either side of the head form above the eyebrow line and directed onto the head form through the visor. Darkening the room helped to minimize visor glare.

Each image frame was frozen on the computer monitor using Adobe Premiere Pro 1.5 (San Jose, CA). Close and careful scrutiny was needed to locate visually the fog on each frame. Sometimes the fog appeared as ghostly fingers (during constant flow) and other times as a wispy cloud (breathing). Pulsing of the LED visible on each frame was used to help determine corresponding times and flow rates from the breathing machine and PAPR blower.

Drawings were made of flow pathways by illustrating the sequences of fog locations on a frame-by-frame basis. Specifically, the fog front was followed from one frame to the next to determine where the flow pathway led.

Net flow rates were calculated by subtracting blower flow from breathing machine flow; this represented overbreathing (or leakage) air flow coming from the outside without passing through the PAPR filter. Inhaled volume was determined by accumulating breathing machine inhalation flow rate with time.

RESULTS

Both respirators showed fog leakage under certain conditions. Shown in Figure 1 is the head form with the LED and thread located in the mouth area. The respirator in this figure is the Centurion MAX. Puffs of fog can be seen in the figure. To construct the drawings of flow pathways, these puffs of fog would have been followed frame-by-frame from their first entrances into the face area until they either reached the mouth or were blown out of the face area by the blower.



Figure 1. One frame of a video taken during a fog challenge test. This picture shows fog inside the face area of the Centurion MAX. The picture is of the black head form mouth area with green LED in the region of the upper lip and fluttering string at the base of the bottom lip.

The scarf seemed to make a big difference, because fog was only apparent behind the face shield for the Centurion when breathing flow rate exceeded blower flow rate. The Racal device without the scarf was filled with fog under all conditions (Figure 2), whether or not the blower was operating, or when the blower was operating and there was no inhalation flow rate (i.e., breath-holding). There was a narrow two-inch strip in the center of the face from the blower outlet at the top of the forehead in the helmet of the Racal to the bottom of the chin that was free of fog when the blower was operating (Figure 3). Vigorous mixing of the fog leaking in from the periphery filled the remainder of the face area with fog and made further visual analysis difficult.

There were apparent regions of turbulence inside each face shield, as evidenced by vortices visible in the fog, which tended to draw outside air into the face piece. For both respirators, when fog entered beneath the face shield from the periphery, it appeared to flow to the front, hit the face shield, and curve back toward the mouth. Different layers of fog flowing in different directions were apparent simultaneously.

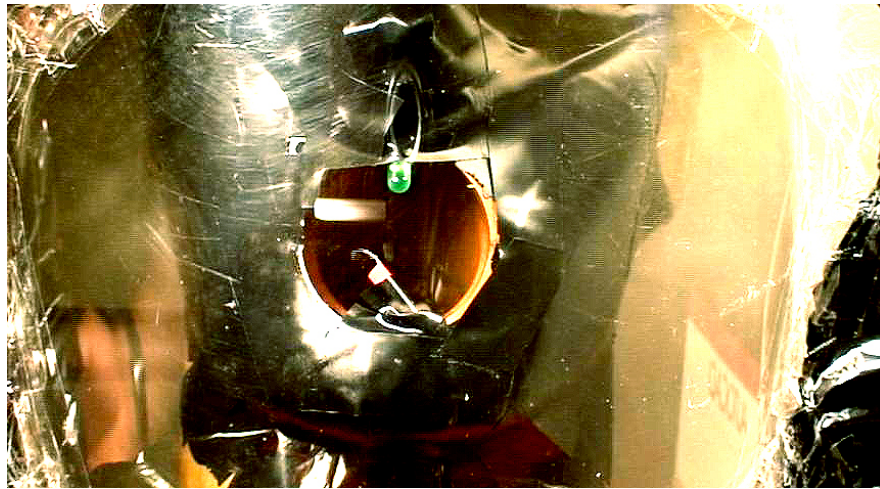


Figure 2. This frame shows the Racal device with fog inside the face shield that persisted whether the blower was operating or not, leaving only about a two-inch strip in the center of the face shield apparently free of fog. The fog can be more clearly seen on the right side of the photo.

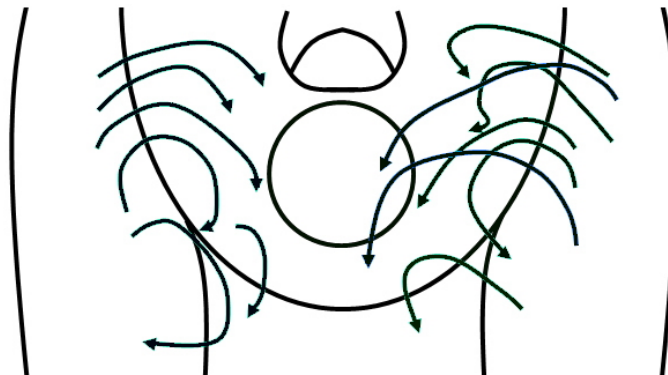


Figure 3. This is a schematic drawing of fog that was drawn inside the Racal face shield whenever the blower was on whether or not the wearer was inhaling. There was a narrow strip vertically in the center of the face shield that did not have a high concentration of fog.

Flow pathways inside the Centurion were charted with the blower off and steady inhalation flow rate set at 18 L/min (Figure 4). Some leakages began at gaps between the visor scarf (not shown in the diagram), and head form near the chin and under the ears. Fog flowed across the face and into the mouth. When the blower was turned on and steady inhalation flow exceeded blower flow, fog pathways were similar (Figure 5). Fog persisted within the face area as long as inhalation flow rate exceeded blower flow rate and fog was present outside the respirator. Contrarily, when blower flow rate exceeded inhalation flow, fog was swept from the face area.

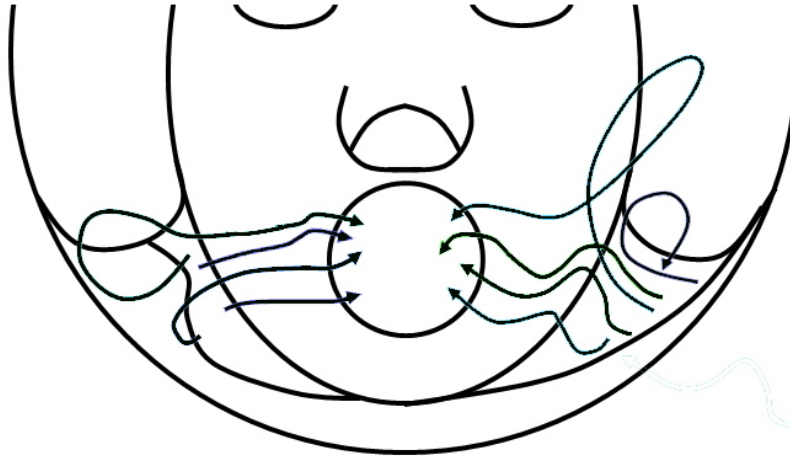


Figure 4. Schematic drawing of fog flow pathways inside the Centurion loose-fitting PAPR. Fog flowed toward the mouth and circled around the eyes and curved back into the mouth when the Centurion blower was off and steady inhalation flow was set at 18 L/min.

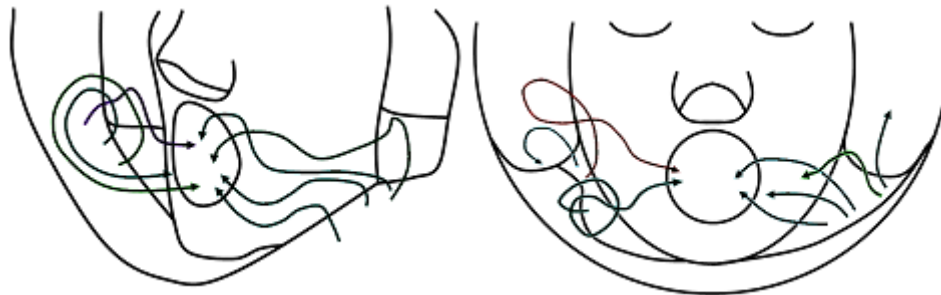


Figure 5. Simplified diagram of fog across the face when the Centurion blower was producing 100L/min and the breathing flow was higher. Each figure depicts a different layer of fog flow within the visor and head form that was only visible when inhalation flow exceeded blower flow.

When the Centurion blower was operating, and the breathing machine was providing intermittent inhaled flow, fog entered the face area only when inhalation flow rate exceeded blower flow rate. Fog was expelled quickly from the face area when blower flow exceeded breathing flow (inhalation), and during exhalation. The leak points and fog pathways were similar to those depicted in Figure 5.

In Figure 6 is a composite diagram of flow rates and volumes in the Centurion MAX along with diagrams of progress of the fog within the face shield. As seen in the upper portion of the diagram, fog did not begin to enter the facepiece until breathing machine flow rate exceeded blower flow rate. Fog

moved toward the mouth as inhalation progressed, and eventually reached the mouth toward the end of inhalation (as indicated by the vertical line). The fog did not reach the mouth until after blower flow exceeded breathing machine flow. The fog inside the face piece dissipated during the exhalation portion of the cycle.

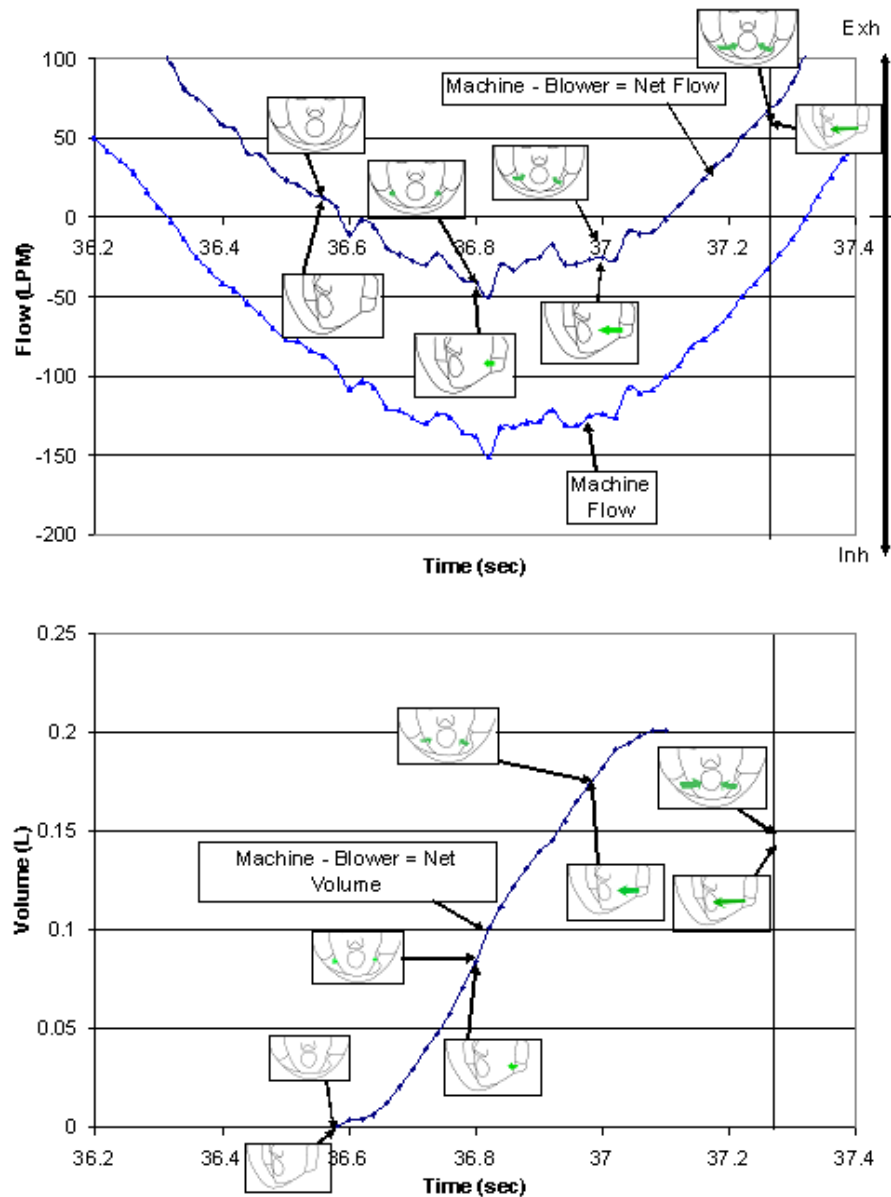


Figure 6. Flow and volume with time when the breathing machine overbreathed the Centurion MAX blower. The upper portion of the diagram represents flow rates of the breathing machine set at a minute volume of 31 L/min at 30 breaths/min. Net flow is the difference between blower flow (nominally 100 L/min) and breathing machine flow. Diagrams inserted at different points of the figure show progress of the fog towards the mouth. The lower portion of the diagram shows breathing machine accumulated inhaled volume during the same time period.

Of much potential interest is the volume of inhaled air that can be breathed before contaminated air reaches the mouth. In order to determine this volume, flow rate during each inhalation was accumulated mathematically and the volume noted when videos indicated that fog first reached the mouth. These tests were repeated for minute volumes of 31, 70, 89, 110 L/min at 30 breaths /min with the Centurion unit.

The results for ten determinations at each minute volume are summarized in Table I. Breathing machine inhaled volume averaged 1.4 L before the fog reached the mouth. Interestingly, this value equals the dead volume of the respirator as measured previously (Mackey et al, 2005). Whereas the fog reached the mouth for all minute volume settings, no fog entered the mouth for the smallest minute volume of 31 L/min. The volumes of contaminated air (air containing fog) inhaled into the breathing machine depended, of course, on tidal volume. These values also appear in Table I. There appeared to be no protection afforded by the dead volume of the Racal AirMate 3; fog reached the mouth and was inhaled at all minute volumes. These data do not appear in Table I.

Table I. Volume of Inhaled Air Before and After the Fog Reached the Mouth at Different Minute Volumes for the Centurion MAX Respirator (Each Value is the Result of Ten Independent Readings)

Minute Volume (L/min)	Tidal Volume (L)	Volume Inhaled Before Fog Reached Mouth (L)	Volume Inhaled After Fog Reached Mouth (L)
31	1.5	1.45 ± 0.045	0.00 ± 0.000
70	2.4	1.23 ± 0.057	0.43 ± 0.054
89	3.0	1.25 ± 0.149	0.81 ± 0.107
110	3.6	1.52 ± 0.065	1.10 ± 0.062
121	4.0	1.55 ± 0.106	1.54 ± 0.095
Avg.		1.40 ± 0.150	

Note: Values given are means ± std. dev. Although fog reached the mouth at 31 L/min, no fog entered the mouth. The volume inhaled before fog reached the mouth and the volume inhaled after fog reached the mouth do not equal the tidal volume; the blower supplies the remaining volume difference.

Head pitch and roll affected the volume inhaled before the fog reached the mouth (Table II). The leak points were similar to the steady state tests with vacuum flow greater than blower flow and the head form was level. As depicted in Table II with the breathing minute volume set at 121 L/minute and the Centurion blower flow set at 100 L/min, the head pitch changed the volume inhaled before the fog reached the mouth. Looking up by 5.9 degrees caused the fog to reach the mouth when 1.4 L was inhaled, whereas looking down by 5.9 degrees caused the fog to reach the mouth when 1.2 L was inhaled. The control condition of zero degrees showed a volume for the fog to reach the mouth to be about 1.6 L. The greatest contaminated (fog/air) volume of 1.74 L was inhaled when the head form looked down 5.9 degrees.

Table II. Volumes of Air Before and After the Fog Reached the Mouth at Several Head Pitch and Roll Angles (Each Value is the Result of Ten Independent Readings, Breathing Minute Volume Was Set at 121 L/min with Tidal Volume of 4.0 L, and the respirator used was the Centurion MAX)

Condition	Volume Inhaled Before Fog Reached Mouth (L)	Volume Inhaled After Fog Reached Mouth (L)
Level	1.55 ± 0.106	1.54 ± 0.095
Down 5.9°	1.19 ± 0.093	1.74 ± 0.051
Up 5.9°	1.45 ± 0.256	1.55 ± 0.202
Side 4.8°	1.70 ± 0.090	1.39 ± 0.073

Note: Values given are means ± std. dev.

DISCUSSION

There are two assumptions made with loose-fitting PAPRs that relate to this work. The first is that a loose-fitting PAPR with the blower operating offers respiratory protection, and the second is that once inhalation flow rate exceeds blower flow rate there is no further protection. Both proved to be incorrect in this study. The Racal AirMate 3 without a scarf to partially confine air inside the face area had fog sucked into the face area by flow turbulence. We can conclude that this respirator would offer very little protection even under conditions of light exertion and high blower flow rate, and this observation correlates well with the previously reported very small protection factor of 1.2 (Johnson et al, 2011). The Centurion MAX, with scarf in place, offered an average of about 1.4 L of tidal volume before contaminated air would have been inhaled. This 1.4 L corresponds to the tidal volume present during moderate exertion, and so can be significant. Tidal volumes during heavy exertion can reach typical levels of 2-2.5 L (Johnson, 2007); these respirators would not afford adequate protection under these circumstances.

Even so, the range of measured inhaled volumes before contamination reached the mouth was 1.13 L to 1.71 L. In order to protect the head form from fog deposition under all measured conditions, tidal volumes should not exceed 1.13 L. Different humans have different facial configurations (and, presumably, respirator dead volumes) and some variability in placement of the helmet and scarf. Humans also tilt their heads and bodies, and move around. Tilting the head form was found to affect protective volume of the Centurion MAX. The conclusion from all this is that there can be some protection afforded by this respirator, but that some safety factor should be applied in order to give a conservative estimate of protective dead volume. Based upon measurements made in this study, and taking into account the fact that the Centurion MAX is often used where the contaminant threat is not high, a protective dead volume of 1.0 L might be suggested. By this we mean that if tidal volumes exceed 1.0 L then no protection can be assured. One liter tidal volumes are encountered with very little exertion, so this recommendation is very restrictive.

Previous testing (Johnson et al, 2011) has shown that the Racal AirMate 3 respirator offers almost no protection against airborne contaminants (protection factor of 1.2), and the Centurion MAX offers only modest protection (protection factor of 4). The results from this flow visualization experiment demonstrate why this is so. What the results from this present study show is that flow pathways are very important in determining the time (and thus the inhaled protective dead volumes) for contaminants to reach the mouth. The longer the leakage flow pathway, the more leakage that can be tolerated before the human wearer is exposed to contaminated air. Thus, these leakage flow pathways should be as curved

and contorted as possible, something that was found to be true in the Centurion MAX respirator. This would be true whether the PAPR was loose or tight-fitting, as long as contaminant leakage was possible.

The same study (Johnson et al, 2011) showed that PAPR blowers do not need to supply more instantaneous clean air than is inhaled at any time. Blowers only need to: 1) supply enough air to slow over-breathed contaminated air (leakage) so that it doesn't reach the mouth during inhalation, and 2) completely sweep contaminated air from the facepiece during exhalation. The Racal AirMate 3 blower did neither of these two things. It seemed to cause enough turbulence under the respirator shield to draw outside air into the breathing zone.

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 block contaminated air from entering the vicinity of the mouth.

Mackey et al. (2005) published a report about overbreathing a multifunction, loose-fitting PAPR, the Centurion MAX (Martindale Protection; Thetford, Norfolk, UK). They reported that all sixteen 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, that is, if the entire 1.4 L consisted of uncontaminated air that was inhaled before contaminated outside air reached the mouth, then the problem of overbreathing would be minimal. This condition would have required diffuse, nonpreferential flow of outside air into the facepiece. It would also require that flow pathways be straight from the leaks to the mouth. Observation of leakage flow pathways inside the PAPR facepiece would thus largely define whether or not leakage of contaminated air poses a threat to the wearer.

Koh et al (2011) measured inward leakage volumes for several tight-fitting PAPRs using glycerol fog and a fiber optic device at the breathing machine mouth to determine when the fog was to be inhaled. They concluded that almost 1.4 L of air had to be inhaled before fog, representing contaminated air, could reach the mouth. This volume of air they termed the protective dead volume of the respirator.

Johnson et al (2008) published a study on human subject testing of the Centurion MAX respirator. They integrated breathing flow rates exhibited by exercising subjects inside a fog-containing chamber, and concluded that, if tidal volume did not exceed 1.1 L, then fog was not inhaled. Protective volume results in this present study are about the same as for the previous study. What this present study has accomplished is that it has substantiated previous results and demonstrated how the protective dead volume is formed. The flow path taken by contaminated air as it enters the facepiece until it reaches the mouth is very important.

In comparing the Racal and Centurion, the benefit of some kind of face seal is very apparent. The Centurion, which contains both a loose face seal around the temporal bone and a loose seal around the mandible (the temple and jaw), limits the free motion of the contaminants from entering the visor area. However, when over breathing starts, the fog enters the visor area around the ramus and mandible. From visual observation, the fog that entered the visor due to over breathing seems to dissipate within the visor during exhalation. Whether all the fog that entered the visor was evacuated during the exhalation cycle is unknown.

One aspect about loose-fitting PAPRs that was underscored by this test is that it is difficult ahead of time to predict the contaminant threat faced by the wearer of one of them. One would think that the presence of flow from a blower would protect to some extent, but these and other results have shown that protection comes from enclosure of a certain volume, whether that enclosure be loose or tight. The presence of the Centurion MAX scarf makes the Centurion much more protective than the Racal, even though the Racal blower supplied a higher flow rate. Although proper placement of the scarf was not

investigated, there is much more to be determined with further study. Certainly the wearer should be made aware of the importance of this piece of cloth.

A quick experiment was performed using the Centurion without its scarf. Fog reached the mouth quicker without the scarf; 1.2 L of air was inhaled before fog reached the mouth without the scarf as compared with 1.4 L with the scarf. The fog generally entered the facial volume in nearly the same place with or without the scarf. These results should be taken very lightly, however, because they only point to the need for further investigation.

If these respirators protect minimally at best, why would workers want to wear them? Aside from the dubious psychological assurance of a feeling of some protection, these respirators may help to cool the face and make it easier to work in hot environments. PAPR facial cooling has previously been shown to extend performance times and facial comfort of wearers walking on treadmills (Johnson et al, 2005).

The accumulation of the residue drawn in by the over-inhaled air may interfere with vision. One side effect of fog entering the visor area of the PAPR was that the inside of the visor became deposited over time with food grade polyfunctional glycerol. One can imagine dusty or oily ambient conditions where this may happen while the respirator is being worn.

If anyone were to try to duplicate these results, they might be interested in our method to produce fog. Several different particle generation schemes were considered for these tests. One that was attempted and failed was to introduce cold, moist outside air into warm, moist air resident inside the face shield. The expected fog never formed. Another scheme was to burn incense candles and hold them near the PAPR periphery. This method was successful in that the smoke could be seen entering the face piece and flowing to the mouth. However, it had the disadvantage that points of entry of smoke into the facepiece were not spontaneous, but depended upon where the candle was held. Aerosolized mineral oil was also attempted. The particles generated by the oil were dense and diffuse. This method had much to recommend it, but left an oily residue on all surfaces contacted by the smoke. Eventually, a glycerol fog was generated with a machine designated for theatrical use.

The public health implications of these results are great. Protection factors assigned to classes of respirators need to be checked under actual wearing conditions that allow for leakages, and measurements of contaminants should be referenced to the mouth and nose of the wearer rather than taken as average values inside the facepiece. If possible to produce, flow pathway visualization inside the facepiece can help to indicate deficiencies in protection against leakages. Better respirators can then be designed or remedial actions plotted to improve protection. Many wearers are unaware of the actual protection afforded by any given respirator under actual conditions. It is the responsibility of manufacturers, purchasers, specifiers, and certifiers to assure that respirators protect wearers to the best possible extent.

CONCLUSIONS

The small protection factors exhibited by these loose-fitting PAPRs seem to be explained by flow pathways of leakage into the facepieces. When the flow patterns are curled and contorted, the path from the leakage point to the mouth is longer than it would be if the flow path were straighter. Longer flow pathways allow more contaminated air to be leaked before it reaches the mouth. These loose-fitting PAPRs cannot be expected to provide protection against realistic levels of ambient contamination. What little protection is afforded depends on the presence of a scarf and head position as they influence the path of flow under the face shield. The blower is no guarantee of protection.

Acknowledgement

This work was funded in part by the National Institute for Occupational Safety and Health (NIOSH) Contract 200-2002-00531.

REFERENCES

- Johnson, A. T., 2007, *Biomechanics and Exercise Physiology: Quantitative Modeling*, Taylor and Francis, Boca Raton, FL.
- Johnson, A. T., F.C. Koh, S. Jamshidi, and T.E. Rehak, 2008, Human Subject Testing of Leakage in a Loose-Fitting PAPR, *Journal of Occupational and Environmental Hygiene*, vol. 5, pp. 325-329.
- Johnson, A. T., F. C. Koh, W. H. Scott, Jr., and T. E. Rehak, 2011, Using CO₂ to Determine Inhaled Contaminant Volumes and Blower Effectiveness in Several Types of Respirators, *Journal of Environmental and Public Health*, vol. 2011, Article ID 402148, <http://downloads.hindawi.com/journals/jeph/2011/402148.pdf>
- Johnson, A. T., K. R. Mackey, W. H. Scott, F. C. K, K.Y.H. Chiou, and S. J. Phelps, 2005, Exercise Performance While Wearing a Tight-Fitting Powered Air Purifying Respirator with Limited Flow, *Journal Occupational and Environmental Hygiene* 2: 368-373.
- Koh, F. C., A. T. Johnson, and T. E. Rehak, 2011, Inward Leakage in Tight-Fitting PAPRs, *Journal of Environmental and Public Health*, vol. 2011: Article ID 473143, <http://downloads.hindawi.com/journals/jeph/2011/473143.pdf>
- Mackey, K. R. M., A. T. Johnson, W. H. Scott, and F. C. Koh, 2005, Overbreathing a Loose-Fitting PAPR, *Journal of the International Society of Respiratory Protection*, vol. 22, pp. 1-10.