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Sixteen subjects exercised at 80–85% of maximal aerobic capacity on a treadmill while wearing a tight-fitting, FRM40-Turbo Powered Air Purifying Respirator (PAPR). The PAPR was powered by a DC power supply to give flow rates of 0%, 30%, 66%, 94%, and 100% of rated maximum blower capacity of 110 L/min. As flow rate was reduced, so was performance time. There was a 20% reduction in performance time as blower flow changed from 100% to 0% of maximum. Significant differences in breathing apparatus comfort and facial thermal comfort were found as flow rate varied. It was concluded that inadequate blower flow rate decreases performance time, facial cooling, and respirator comfort.

Keywords PAPR, respiration, respiratory protection

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The results published in this article are solely the responsibility of the authors.

INTRODUCTION

Powered air-purifying respirators (PAPR) are the protection of choice for a broad range of wearers and tasks because they require less inspiratory effort to draw air across the filters, and they blow cooling air across the face in warm environments. As long as pressure inside the facepiece remains positive, protection provided by a PAPR should exceed that of a nonpowered air purifying respirator (APR); faceseal and expiratory valve leakage should be of little consequence.

As long as respiratory flow rates do not exceed blower flow rates, apparent inspiratory resistance of a PAPR should be slightly negative. That is, breathing in the PAPR should be easier than it would be if just inhaling without wearing a respirator. The positive pressure inside the facepiece assists the respiratory muscles to draw air into the lungs.

The same effect that assists inspiration works against expiration, so PAPRs should make it somewhat harder to exhale than if no respirator were being worn. This effect would most likely be more noticeable at rest than during strenuous work because exhalation at rest is nearly passive (no active muscle contraction is involved for exhalation at rest), but exhalation during work is active (abdominal muscles contract to push air out). Exhaling against a positive pressure is easier and less noticeable if muscles can produce somewhat greater force to compensate for the increased pressure.

Based on anecdotal evidence, the increased exhalation pressure does not seem to cause a problem for wearers. This may be because of two factors: (1) PAPR may be worn mostly during strenuous work when exhalation is active, and (2) the presence of the exhalation valve limits the positive pressure inside the facepiece to a low value (typically 2.6 cm H_2O at 85 Lpm). Of the two, the second is likely to be more important to PAPR wearers.

Peak flows during strenuous work are likely to exceed blower capacity. Also, PAPR worn for long periods of time are likely to have discharged batteries, and these would have less power to deliver the specified airflow. In either case, overbreathing the air capacity of a PAPR blower is likely. Overbreathing the fan would cause the wearer to have to breathe through the resistance of the filter, fan, and tubing. How this resistance affects performance is not easy to determine.

Attempts to analyze this situation to predict the outcome of overbreathing a tight-fitting PAPR demonstrate its complexity. An equivalent electrical schematic for the PAPR on a wearer is shown in Figure 1. The blower is diagrammed as a pressure source P_b, and the flow through the blower is given by $\dot{V}_b$. Resistance of the blower, filter, and tubing is indicated by the resistance labeled R_f. Blower flow can take one of two paths: it either is breathed ($\dot{V}_r$) or leaked through the exhalation valve ($\dot{V}_e$). The respiratory system of the wearer is represented by a pressure source (P_r) in series with respiratory resistance (R_r). The exhalation pathway is represented by a diode (allowing one-way flow only) and a resistance (R_e). Mask facepiece pressure is given as the symbol P_m. For simplicity, the resistances R_f, R_r, and R_e, and the blower pressure P_b are assumed to be constant.

All flows flowing into the node marked P_m are assigned a positive sign convention. In this sense, $\dot{V}_e$ will be negative and

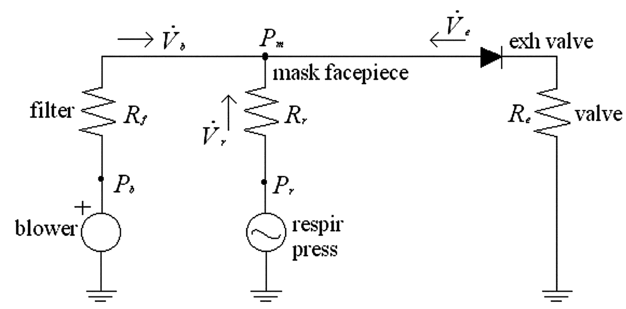

FIGURE 1. Equivalent electrical circuit diagram for the PAPR as worn

$\dot{V}_r$ will oscillate between positive and negative values. With these definitions and conventions, a series of equations can be written:

$$\dot{V}_b + \dot{V}_r + \dot{V}_e = 0 \quad \textbf{(1)}$$

$$\dot{V}_r = \frac{P_r - P_m}{R_r} \quad \textbf{(2)}$$

$$\dot{V}_b = \frac{P_b - P_m}{R_f} \quad \textbf{(3)}$$

$$\dot{V}_e = \frac{-P_m}{R_e} \quad \text{for } P_m > 0 \quad \textbf{(4a)}$$

$$\dot{V}_e = 0 \quad \text{for } P_m \leq 0 \quad \textbf{(4b)}$$

There are two flow domains of interest: (1) no overbreathing ($P_m > 0$), and (2) overbreathing ($P_m \leq 0$). The condition of no overbreathing includes exhalation and some part of inhalation. Overbreathing only occurs during strong inhalation.

Algebraic manipulation yields the following for face piece pressure:

$$P_m = R_e(\dot{V}_b + \dot{V}_r) \text{ no overbreathing} \quad \textbf{(5)}$$

$$P_m = P_b + \dot{V}_r R_f \text{ overbreathing} \quad \textbf{(6)}$$

and respiratory pressure:

$$P_r = \dot{V}_r R_r + R_e(\dot{V}_b + \dot{V}_r) \text{ no overbreathing} \quad \textbf{(7)}$$

$$P_r = P_b + \dot{V}_r(R_r + R_f) \text{ overbreathing} \quad \textbf{(8)}$$

One effect of overbreathing is to shift the reference pressure for both P_r and P_m from atmospheric ($P = 0$) to blower pressure (P_b).

The results of this analysis are diagrammed in the two graphs of Figure 2. The upper graph shows facepiece pressure plotted against the excess flow through the blower ($\dot{V}_b + \dot{V}_r$). Overbreathing occurs when excess flow becomes negative. Otherwise, no overbreathing occurs when ($\dot{V}_b + \dot{V}_r$) is positive. The slope of the line is just R_e for the no overbreathing condition, but for overbreathing it changes gradually to R_f.

The lower graph plots respiratory pressure (P_r) against respiratory flow rate ($\dot{V}_r$). The slope of the line is $\frac{P_r}{\dot{V}_r} = R_r + R_e (1 + \frac{\dot{V}_b}{\dot{V}_r})$ for no overbreathing, and gradually becomes (R_r + R_f) for overbreathing. Zero respiratory flow can occur only if respiratory pressure is maintained at a positive pressure of $P_r = P_m = -R_e\dot{V}_e$ (remember that $\dot{V}_e$ is negative with our sign convention). This graph shows that exhalation is performed against a positive pressure that changes with flow rate, and that at high enough overbreathing rates, filter resistance must be overcome by respiratory pressure.

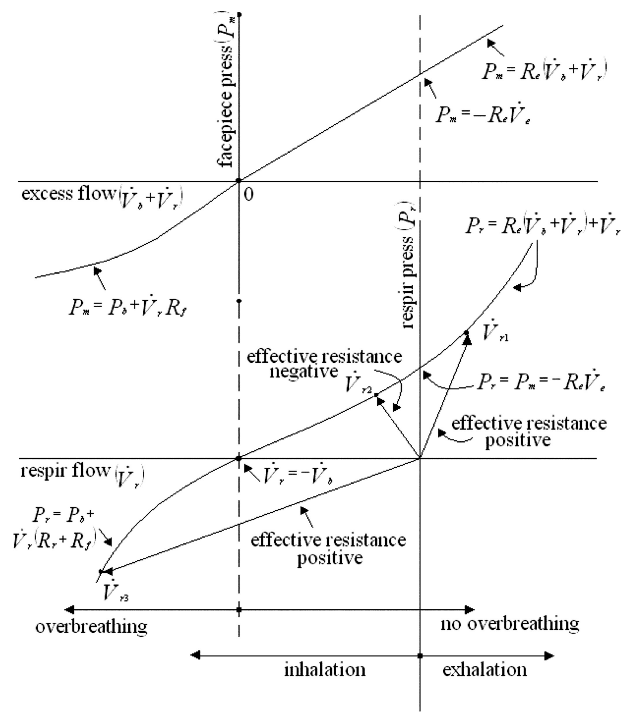

FIGURE 2. Pressure-flow diagrams for the PAPR facepiece (above) and the wearer (below); resistance detected by the wearer varies in magnitude and sign.

The resistances detected by the respiratory system are given by the slopes of the lines drawn from the origin of the lower graph to the points on the curve where the respiratory flow rates appear. The exhalation resistance, drawn to $\dot{V}_{r1}$, is positive and decreasing somewhat as exhalation flow rate increases. The effective inhalation resistance is negative for flow rate $\dot{V}_{r2}$, zero at the point where $\dot{V}_r = \dot{V}_b$, and again positive for $\dot{V}_{r3}$. To make matters even more complicated, blower flow rate ($\dot{V}_b$) may exceed respiratory flow rate ($\dot{V}_r$) within part of each breath and $\dot{V}_b$ may be exceeded by $\dot{V}_r$ during other parts of the same breath.

Previous experimental results have shown that exercise performance times are affected by levels of inhalation[1] and exhalation[2] resistances. In both cases, as respirator resistance increased, performance time decreased linearly. So, the expectation is that overbreathing a PAPR might effectively increase resistance but by how much and to what effect is unknown. For this reason, overbreathing of a tight-fitting PAPR was put to an experimental test.

METHODS

Sixteen volunteer subjects participated in this study, which was approved by the University of Maryland Institutional Review Board. Table I gives demographics for the subjects.

TABLE I. Subject Demographics

Gender	8 males, 8 females
Age (yrs)	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	34.5 ± 9.69

An investigator met with the prospective participant to explain test procedures and methods. The participant was then provided with an informed consent document, a brief medical history form, and a physical activity questionnaire. The participant was asked to complete a physical activity readiness questionnaire (PAR-Q), which determined whether vigorous activity was appropriate.

A maximal oxygen ($\dot{V}O_2$ max) consumption test was performed before experimental treatments were begun on all prospective participants using a motorized treadmill (model 265Q; Quinton, Bothell, Wash.). Participants were asked to warm up and stretch for approximately 5–10 min prior to the start of the test. After the warm-up the participants donned a one-way breathing valve (8932; Hans Rudolph, inc., Kansas City, Mo.) configured with a rubber adaptable mouthpiece. This apparatus was attached to a standard Fleisch #4 pneumotach (Phipps & Bird, Richmond, Va.) and mass spectrometer (model 1100; Perkin Elmer, Pomona, Calif.) to monitor continuous expired airflow. Heart rate measurement was assessed using a standard ECG electrode configuration with the leads connected to a monitoring system (model M1960A; Hewlett-Packard, Palo Alto, Calif.). The initial work rate was established at a speed and grade designed to elicit 70% of the participant's age-predicted maximal heart rate (approximately 60% $\dot{V}O_2$ max). The work rate (speed and grade) was adjusted every third minute until the participant experienced volitional fatigue, failed to display a rise in oxygen consumption rate of at least 150 mL O_2/min in accordance with the increase in work rate, or exhibited cardiovascular responses that contraindicated walking further. Most subjects completed $\dot{V}O_2$ max in about 9–15 min.

Flow rate to the respirator was controlled with a variable voltage power supply in place of the battery. The steady flows resulting from manipulating power supply voltage are shown in Table II and Figure 3. All flow rates were measured with a Fleisch #4 pneumotach inserted in the hose between the blower and unworn facepiece. Flow rate conditions were assigned to each subject in balanced random (Latin square) order.

Each participant was asked to warm up and stretch for approximately 5–10 min prior to the start of each experimental test session. Respirator facepieces were put on the subjects immediately after the warm-up. Face seals were checked for leaks by blocking the inhalation port without the blower hose. Straps were adjusted for comfort and to eliminate leaks. All subjects wore the PAPR blower and filter (FR-57; 3M, St. Paul, Minn.) on their waists without the battery pack. The treadmill speed and grade were set at a work rate eliciting approximately 70% of the individual's age-predicated maximal heart rate. Electrodes were used to monitor heart rate continuously during the test. Work rate was slowly increased within 90 sec to the speed and grade corresponding to 80–85% of the participant's maximal aerobic capacity as predetermined during the $\dot{V}O_2$ max test. On reaching the predetermined speed and grade, the timing was started. The participant was asked to exercise at this intensity until volitional fatigue. These procedures were used in all conditions. Rating of perceived exertion (RPE), breathing apparatus comfort (BACS), facial thermal comfort (FTC), and overall thermal comfort (OTC) were used to objectively gauge fatigue and comfort of the subject during each condition. These scales were assessed every 2 min. Each session took approximately 1 hour from start to the end of a 5-min cooldown period of walking on the treadmill. All tests were conducted in an environmentally controlled laboratory.

TABLE II. Voltages and Corresponding Flow Rates Produced by the Tight-Fitting PAPR

Volts	Flow Rate (L/min)	Percent Max Flow Rate (%)
4.8	109.82	100
4.5	103.46	94
3.28	72.11	66
1.86	33.24	30
0	0	0

RESULTS

Average performance time data appear in Figure 4. Performance times varied from 701 sec to 848 sec. There was a 21% difference from no blower flow to maximum blower flow. Paired t- tests showed statistically significant differences ($p = 0.05$) between the 0% flow condition and either of the two highest flows.

A summary of other measurements is found in Table III. Breathing apparatus comfort (BACS), rating of perceived exertion (RPE), overall thermal comfort, facial thermal comfort (FTC), and heartrate (HR) are given for termination and at the fourth minute into the test. We have found that termination values do not always discriminate among treatments, but sometimes values compared at some time before termination, when all subjects are still participating, do show differences. We have chosen to compare this measure taken at the fourth minute (240 sec).

As an example, consider the BACS, a scale that ranges from 0 (very, very uncomfortable) to 10 (very, very comfortable). Termination values of BACS discriminate between flow rate extremes but are not overall statistically significant. The 4-min BACS is statistically significant at $p = 0.05$ as determined by analysis of variance (ANOVA). Paired t-tests indicate that

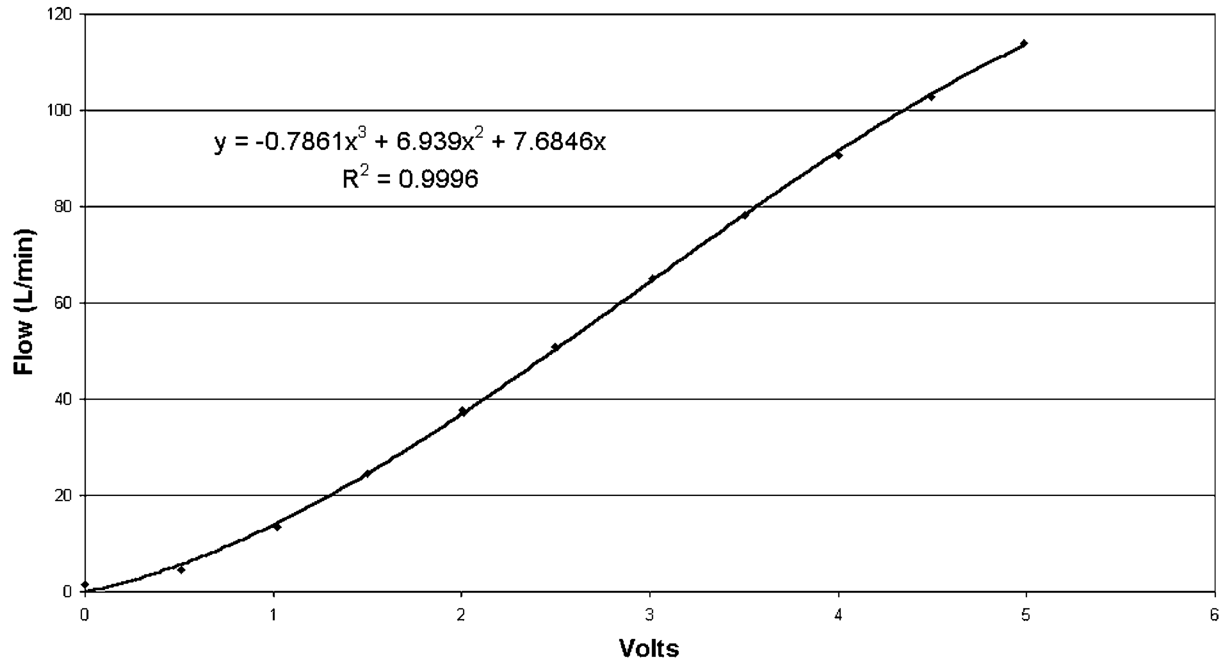

FIGURE 3. Steady flow rates of the tight-fitting PAPR and the third order polynomial function that best fits the data

quite a few paired comparisons are statistically significant at $p = 0.05$. The BACS value of 3.25 indicates "fairly uncomfortable," whereas the BACS value of 5.38 indicates "fairly comfortable."

The other statistically significant effect is the FTC at 4 min. Facial thermal comfort ranges from 5.75 (warm) at 0% flow to 4.56 (neutral) at 100% flow. OTC at 4 min appears to have been affected somewhat by FTC at 4 min, although the face covers

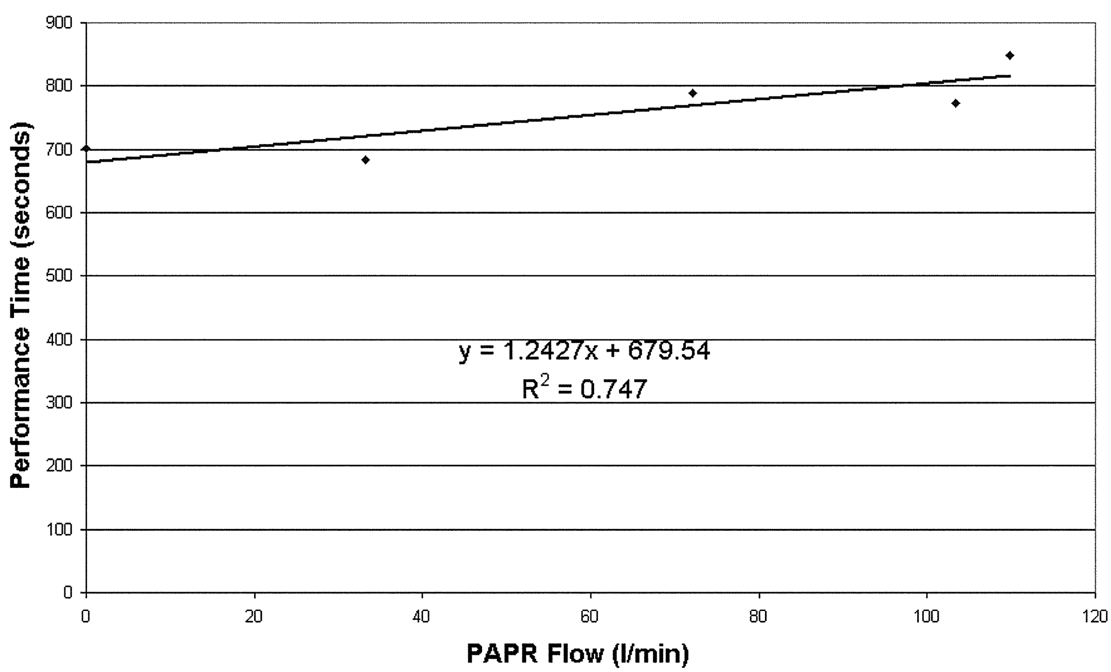

FIGURE 4. Average performance times for work at different flow rates. Performance times decreased as flow rate decreased, indicating that inhalation resistance was the most important determinant of performance.

TABLE III. Summary of Test Data

(Flow Rate (L/min)	0	33	72	103	110
Performance time (sec)	$701^{A} \pm 477$	$683^{B} \pm 367$	790 ± 492	772 ± 365	$848^{A,B} \pm 122$
BACS (term)	$1.75^{A} \pm 0.48$	$1.50^{B} \pm 034$	$2.00^{C} \pm 0.45$	2.25 ± 0.51	$3.00^{A,B,C} \pm 0.55$
BACS* (4 min)	$3.25^{A,B,C} \pm 0.48$	$3.60^{D,E,F} \pm 0.45$	$4.25^{A,D,G} \pm 0.36$	$4.62^{B,E,H} \pm 0.40$	$5.38^{C,F,G,H} \pm 0.54$
RPE (term)	17.7 ± 0.53	18.1 ± 0.28	18.3 ± 0.30	18.1 ± 0.29	18.2 ± 0.25
RPE (4 min)	$14.8^{A} \pm 0.63$	14.5 ± 0.49	$14.2 \pm .53$	14.2 ± 0.41	$14.1^{A} \pm 0.59$
OTC (Term)	6.12 ± 0.22	6.12 ± 0.20	6.31 ± 0.18	6.31 ± 0.22	6.12 ± 0.22
OTC (4 min)	$5.25^{A} \pm 0.23$	$5.27^{B,C} \pm 0.23$	5.12 ± 0.22	$4.88^{B} \pm 0.26$	$4.69^{A,C} \pm 0.28$
FTC (term)	6.44 ± 0.18	6.62 ± 0.12	6.44 ± 0.18	6.38 ± 0.29	6.31 ± 0.28
FTC* (4 min)	$5.75^{A,B,C} \pm 0.21$	$5.47^{D,E,F,H} \pm 0.24$	$5.06^{A,D,G} \pm 0.25$	$4.75^{B,E,G} \pm 0.27$	$4.56^{C,F,H} \pm 0.27$
HR (term)	$184^{A} \pm 2.6$	183 ± 3.0	185 ± 2.9	186 ± 2.6	$189^{A} \pm 3.4$
HR (4 min)	$178^{A} \pm 2.3$	$173^{B} \pm 3.8$	175 ± 2.8	$177^{B,C} \pm 2.3$	$179^{A,C} \pm 3.1$

Notes: Data presented are means ± standard deviation. Superscript letters indicate statistically significant pairs at p = 0.05 from paired t-test. *Denotes overall statistically significant effect at p = 0.05 from ANOVA.

only 5% of body surface area. RPE and HR at termination differed little among flow rates, which indicates that subjects expended about the same amounts of effort for each flow rate and demonstrates that performance times can be given credence.

DISCUSSION

The INTRODUCTION section summarizes what was known before testing began. Since there was no prediction of the experimental outcome, the results of this experiment cannot be said to conform to expectations. Nonetheless, it was anticipated that lower blower flow rates would cause the wearer to breathe through the filter resistance in increasing amounts. Based on previous studies, this would mean lower performance times. This informal anticipation was confirmed by the results.

As flow rate decreased, the beneficial effect for exhalation appears to be less than the detrimental effect for inhalation, so the overall effect is a performance penalty. Whether this penalty is significant in the workplace depends on many factors. A 20% reduction in performance time for a 100% reduction in blower flow rate may be avoided if the battery is maintained in a relatively high state of charge. However, during emergencies when times of physical activity may be lengthened significantly, respiratory flow rates are higher than normal, and the luxury of battery recharge cannot be availed, then a 20% reduction in performance capability could be critical.

Peak respiratory flow rates may be 400 L/min or more depending on the person and the work rate. It is clear that this PAPR does not supply sufficient air to meet this demand. Hence, even if the battery is fully charged and the blower is working at full capacity, the wearer must expend some effort to breathe against the filter resistance. Judging from results from this study, some performance penalty could be expected.

The reason for PAPR wear preference is given by the BACS and FTC scores. PAPR are significantly cooler and more comfortable, giving the wearer more capacity to work. If the wearer feels better she or he will probably have a better attitude about work. Ambient air in our laboratory was at a comfortable temperature (18–20°C). The cooling effect of the blower air might be greater or less depending on ambient temperature, but evaporation of facial sweat could still be very important. The Spielberger State-Trait Anxiety Inventory[3] was given to the subjects before and after each session (Table IV). State anxiety increased for all flow rates but no differences achieved statistical significance. The smallest pre-post differences were for the highest flow rates.

TABLE IV. Average State Anxiety Scores Before and After Each Test Session

PAPR Flow Rates (L/min)	State-Trait Anxiety Inventory Pre	State-Trait Anxiety Inventory Post	Significance Level
0	34.47 ± 6.85	37.40 ± 9.02	0.16
33.24	34.00 ± 7.09	37.75 ± 10.29	0.12
72.11	32.38 ± 7.80	36.94 ± 8.43	0.06
103.46	33.81 ± 8.44	36.50 ± 9.56	0.20
109.82	33.40 ± 9.96	33.80 ± 8.74	0.45

Note: Data presented in means ± standard deviation.

Although the conditions of this study were not those expected in an actual workplace environment, the results can be useful. A battery that dies completely and shuts off the blower is not likely to happen in a well-regulated environment, but all devices are inclined to fail at some time.

When conducting a scientific experiment, the protocol needs to be most sensitive to the anticipated effects of the treatments. We usually test at 80–85% $\dot{V}O_2$ max when we want to see whether treatments primarily affect the respiratory system. Likewise, we impose extreme conditions to reduce the relative importance of natural variation in responses. Overall trends are much easier to see if noise is relatively small. One can reduce relative noise by either using a very homogeneous group of subjects and testing procedures (not easily done) or by imposing a wide range of treatment levels.

CONCLUSIONS

1. When flow rates are not adequate there is a performance decrement.
2. Reducing blower air flow rates decrease PAPR comfort and facial cooling.

ACKNOWLEDGMENTS

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