# Peak Inhalation Air Flow and Minute Volumes Measured in a Bicycle Ergometer Test

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## ABSTRACT

There are many important physical and physiological factors to consider when designing, testing and certifying respiratory protective devices. In 1943, Leslie Silverman identified two of the most important factors to be the maximum rate at which air flows during each inspiration and the length of time during which this maximum air flow continues. Despite his finding, there are few papers in the literature that have actually reported the inhalation flow rate. Mostly when flow rates are reported they had been arrived at by a formula. This paper reports respiratory data measured for various respiratory protective devices (RPD) at various metabolic rates, with and without speech. As particle filters are velocity-dependent, the flow rate through the filter will dictate the overall performance of the RPD. Thus, we were specifically interested in the minute volume and the peak inhalation airflow (that is, the highest flow reached during each breath) measured at the work rates applicable to tasks performed by first responders. The data obtained for all test subjects made it possible to analyze the minute volume ($V_I$, measured in L/min), and the peak inhalation airflow (PIAF, measured in L/min). Seven test subjects (mean age = 30.3 years, standard deviation = 13.8) participated in this study pedaling a bicycle ergometer at various work rates between 50 and 200 W. Five full-face masks with different inhalation and exhalation characteristics were used. The average minute volume inhaled was 55.3 L/min (n=203) without speech. When subjects were asked to read aloud as when talking normally, the value was significantly lower 45.1 L/min (n=203). The average PIAF without speech was 169 L/min, and with speech 266 L/min. There were also significant reductions in $V_I$ and PIAF depending on the characteristics of the respiratory protective devices. The average ratio (i.e., PIAF/ $V_I$) in all data was 4.4 (range = 3.9 - 5.0). The high PIAF values observed in this study can have a significant impact on the performance of respirators. Thus, we perhaps need to reconsider how respiratory protective devices should be tested.

**Keywords: peak inhalation air flow, PIAF, ergometer, respiratory protective device, RPD, speech**

## INTRODUCTION

The pressure drop in the face enclosure caused by the inspiration air flow (IAF) governs the performance of a respiratory protective device (RPD) (Clayton *et al.*, 2002). If the RPD is a negative pressure device, the negative pressure in the face enclosure affects the seal against the face (and hence the RPD's capability to prevent contaminants from leaking into the face enclosure). If the fit is good, the negative pressure will cause the outside air pressure to push the mask more firmly against the face and thereby decrease the risk of inward leakage. On the other hand, if there is a small leak, the negative pressure will only increase the leakage into the face enclosure (Bostock, 1985; Dahlbäck and Novak, 1983; Hinds and Bellin, 1987; da Roza *et al.*, 1990; Holton *et al.*, 1987).

In the case of powered air purifying respirators (PAPR) and positive pressure demand respirators, a similar difficulty prevails, namely, the limited capacity to maintain a sufficient amount of supplied air to the user. If the IAF is higher than the supply capacity while wearing powered and air supplied RPDs, a negative pressure will most likely form in the face enclosure. This will increase the risk of face seal leakage and possibly result in decreased protection. The extent of the leakage depends on the level and duration of the negative pressure in relation to the total breathing cycle (Bostock, 1985; Clayton *et al*., 2002; Dahlbäck and Novak, 1983; da Roza *et al*., 1990). In addition to causing a risk of inward leakage, an increase in negative pressure will also have a degrading effect on the wearer of the RPD, not only in regard to the ability to perform a task (Johnson *et al*., 1999), but also to the subjective capability of wearing the RPD all the time while the RPD user remains in the contaminated area (Silverman and Billing, 1961; Silverman *et al*., 1951). This type of equipment is tested and approved according to existing standards (da Roza *et al*., 1990; Dahlbäck and Novak, 1983; Verstappen *et al*., 1986).

In regards to particle filters which are velocity-dependent (Revoir and Bien, 1997) and typically tested at 85-95 L/min constant flow, the flow rate through the filter will dictate the overall performance of the RPD.

With the view to provide an aid in the evaluation of existing and future standards testing criteria and methods, this study was designed to investigate the IAF in humans performing physical work while wearing a respirator. Two major facets of IAF were of particular interest, namely inhaled tidal volume and peak inhalation air flow, and especially how these two facets were influenced by physical and physiological factors such as respirator differences (inhalation/exhalation resistance), the presence or absence of speech, and different work rates.

# MATERIAL AND METHODS

## Test Subjects

This study was performed at the S.E.A. Human Subject Test Laboratories in Sydney, Australia. Seven test subjects, 6 male and 1 female, participated in the study. No beard growth was allowed. General physical fitness was established with each subject before the test. Physiological characteristics of the subjects who participated in this study are summarized in Table I.

**Table I. Summary of Physical Characteristics of the Subjects Performing the Tests (n=7)**

| Subject Characteristics | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|
| **Age (years)** | 30.3 | 13.8 | 17 | 51 |
| **Weight (kg)** | 78.0 | 13.0 | 62 | 96 |
| **Height (cm)** | 181.9 | 7.4 | 173 | 193 |
| **Predicted $V_{O2\,max}$ ($ml{\cdot}kg^{-1}min^{-1}$)** | 41.3 | 6.8 | 29.7 | 50.0 |
| **Predicted max $VO_2$ (L/min)** | 3.16 | 0.40 | 2.6 | 3.7 |

Note: $V_{O2\,max}$ were predicted using Åstrand *et al*. (2003) nomogram.

## RPD Used for This Test

Five full face masks with different performance characteristics were used (Table II). The first RPD was a US Military M40 (Supplied by the US Marines, Indian Head, Maryland, USA) full face mask with a US

C2A1 military filter. The second RPD was an SEAFF (The SEA Group, Branford, CT, 06405, USA) full face mask with a domestic preparedness (DP) filter. The third RPD was an SEASMF (The SEA Group) full face mask with side-mounted DP filter. The fourth RPD was a SR200A1 (Sundström Safety AB, Lagan, Sweden) silicone full face mask with two exhalation valves. The filter used for the flow measurement was an A1 (organic vapour). The fifth RPD was SR200 (Sundström Safety AB) silicone full face mask with two exhalation valves and no filter.

**Table II. Performance Characteristics of the RPDs Used**

| Respirator Model | | Test Flow Rate | | | | | |
|---|---|---|---|---|---|---|---|
| | | 85 L/min | 100 L/min | 200 L/min | 300 L/min | 400 L/min | 500 L/min |
| **M40** | Inhalation (millibar) | 2.8 | 3.5 | 8.4 | 15.5 | 23.7 | 32.0 |
| | Exhalation (millibar) | 1.9 | 2.1 | 4.6 | 7.0 | 8.0 | 12.0 |
| **SEAFF** | Inhalation (millibar) | 2.8 | 3.6 | 8.5 | 15.4 | 23.5 | 33.0 |
| | Exhalation (millibar) | 0.9 | 1.1 | 1.6 | 3.5 | 5.9 | 9.0 |
| **SEASMF** | Inhalation (millibar) | 2.9 | 3.7 | 8.3 | 13.3 | 19.5 | 26.3 |
| | Exhalation (millibar) | 0.2 | 0.3 | 0.6 | 1.1 | 1.7 | 2.2 |
| **SR200A1** | Inhalation (millibar) | 0.7 | 0.9 | 3.6 | 6.5 | 10.1 | 13.8 |
| | Exhalation* (millibar) | 0.1 | 0.2 | 0.5 | 1.0 | 1.65 | 2.5 |
| **SR200** | Inhalation (millibar) | 0.4 | 0.6 | 1.6 | 3.3 | 4.65 | 6.2 |
| | Exhalation* (millibar) | 0.1 | 0.2 | 0.5 | 1.0 | 1.65 | 2.5 |

The inhalation resistance in this table includes, filter and the flow meter.
* Two exhalation valves.

## Test Equipment

A portable flow meter was used. The flow meter was designed to measure the resistance over a flow resistor with a linear relationship between flow and resistance from 0 L/min to 600 L/min. The detailed description of the flow measuring instruments has been published previously (Berndtsson and Ekman, 2003). This flow meter was connected to the inhalation port of each respirator.

A bicycle ergometer ("Monark 839E", Monark Exercise AB, Vansbro, Sweden) was connected to a computer, and calibrated in accordance with the manufacturers instructions. A test protocol was developed by means of the software supplied with the bicycle. The heart rate was measured using a heart rate monitor ("POLAR S610", Polar Electro OY, Kempele, Finland), downloading to POLAR software.

## Conditions in the Test Room

The temperature was 23 ± 3 degrees Celsius and relative humidity was 47% ± 5%. All data collected at Ambient Temperature and Pressure, Dry (ATPD) were converted to Body Temperature and Pressure, Saturated (BTPS) for ease of comparison with other data.

## Test Procedures

The subjects were dressed in gym clothing (shorts, t-shirt and sneakers). All test subject where in good health; a physical examination was performed by a medical doctor. An introduction was given as to the procedures of the test, after which the test subjects had an opportunity to familiarize themselves with the different test masks. The test was divided into seven five-minute periods, each with a different external workload. The external workloads used were:

1. 50 W (Walking 3 mph or 5 km·hr$^{-1}$, light industry, housework)
2. 75 W
3. 100 W (Walking 4.53 mph or 7 km·hr$^{-1}$, manual labor, farming, mining, gardening, shoveling)
4. 125 W
5. 150 W (Running 5.5 mph or 9 km·hr$^{-1}$; walking 5 mph or 8 km·hr$^{-1}$; climbing stairs, lumber work, heavy manual work)
6. 175 W
7. 200 W (Running 7 mph or 11 km·hr$^{-1}$, crawl swimming 50 m·min$^{-1}$, exceptionally heavy manual labor)

Energy expenditure (sample of activities) is only approximate. It is a general guide and depends among other things on weight of the subject. The samples listed are based on a body weight of 160 lbs (70-75 kg), (Åstrand *et al*., 2003).

During the first three minutes of each five-minute period, the test subject pedaled the bicycle without interference. This allowed the subject's heart rate and breathing pattern to stabilize. During the fourth minute, the test subject was asked to read aloud *The Rainbow Passage* (AS/NZ 1716:2003) for one minute. The reading was continued for one minute. During the fifth minute (the recovery minute), the subject pedaled without any interference. At the end of the fifth minute, the ergometer automatically increased the workload by 25 W. The protocol was then repeated. The test was terminated by the test officer if the test subject felt uncomfortable, or when 85% of the theoretical max heart rate was reached, whichever occurred first.

The collected data amounted to 83% (n=203) of the potential data. If all test subjects would have completed all work levels with all masks, the total data files would be n=245. All seven subjects could complete the five first work levels 50-125 W with all five masks (n=140). Five subjects completed all five masks at 150 W, one subject completed four masks and one subject completed three masks (n=32). Three subjects completed all five masks at 175 W, two subjects completed four masks, one subject completed three masks and one subject did not complete any tests at this level (n=26). Two subjects completed two masks and one subject completed one mask at 200 W (n=5). As all tests started at 50 W, fatigue could have caused early termination with some test subjects.

## Data Collection

Data were collected for every breath during the entire test, at 50 samples per second. Pulmonary ventilation ($V_I$, minute volume inhaled, L/min) was determined by numerical integration (flow rate by time) and presented as one value for each minute. Peak inhalation air flow, PIAF, (L/min) is the highest flow rate which occurs during the inspiration cycle of a breath. The PIAFs presented in this report are the average measured from all breaths for each test subject and RPD combination during the minute before speech and the speech minute (3$^{rd}$ and 4$^{th}$ minutes).

## Statistical Analyses

Minute volume and peak inhalation airflow were analysed using a four-factor analysis of variance model (ANOVA). Minute volume and peak inhalation airflow were the response/dependent variables.

Respirator models, workload, speech, and subject were the predictor/independent variables. A Duncan multiple range test was performed to determine whether minute volume or peak inhalation airflow varied among the treatment levels. A significance level of 0.05 was used for all tests.

# RESULTS

Tables III to VI summarize minute volume and peak inhalation airflow by respirator, workload, speech, and subject. All four main effects/factors were found to be statistically significant. Significant differences in minute volume and peak inhalation airflow were found among different respirator models (Table III).

**Table III. Summary of Minute Volume ($V_I$) and Peak Inhalation Airflow (PIAF) by Respirator Model**

| Respirator | n** | $V_I$ | | | PIAF | | |
|---|---|---|---|---|---|---|---|
| | | Mean (L/min) | Standard Deviation | Duncan Grouping* | Mean (L/min) | Standard Deviation | Duncan Grouping* |
| M40 | 74 | 54.0 | 21.0 | A | 212 | 62.7 | C |
| SR200 | 86 | 51.3 | 20.6 | B | 248 | 93.3 | A |
| SR200A1 | 81 | 50.7 | 20.9 | B | 224 | 81.0 | B |
| SEAFF | 84 | 48.5 | 19.7 | C | 205 | 69.6 | D |
| SEASMF | 81 | 46.8 | 19.4 | D | 196 | 71.7 | E |

* Means with the same letter are not significantly different from each other.
** n represents the number of data sets (the maximum for each respirator is n=98).

Significant differences in $V_I$ and PIAF were also found among different workloads. Ranking the $V_I$ according to work load (Table IV, Figure 1), resulted in a linear increase of $V_I$ up to 150 W (averaging at 20% per workload increment). At 175 W the increase was 24% and at 200 W the increase was 33%. The average increase in PIAF was 11% up to 150 W, 16% at 175 W, and 28% at 200 W.

**Table IV. Summary of Minute Volume ($V_I$) and Peak Inhalation Airflow (PIAF) by Workload**

| Workload (W) | n** | $V_I$ | | | PIAF | | |
|---|---|---|---|---|---|---|---|
| | | Mean (L/min) | Standard Deviation | Duncan Grouping* | Mean (L/min) | Standard Deviation | Duncan Grouping* |
| 200 | 12 | 105.1 | 20.0 | A | 363.9 | 66.3 | A |
| 175 | 50 | 76.8 | 14.1 | B | 285.1 | 66.7 | B |
| 150 | 64 | 62.3 | 11.6 | C | 246.1 | 67.4 | C |
| 125 | 70 | 51.9 | 9.8 | D | 219.4 | 63.5 | D |
| 100 | 70 | 43.5 | 8.1 | E | 202.9 | 65.1 | E |
| 75 | 70 | 36.0 | 7.7 | F | 185.6 | 65.2 | F |
| 50 | 70 | 29.9 | 6.0 | G | 161.8 | 59.2 | G |

* Means with the same letter are not significantly different from each other.
** n represents the number of data sets (the maximum for each workload is n=70 (35 with speech and 35 without speech)).

The mean $V_I$ for all RPD and all workloads was 55.3 L/min with no speech and 45.0 L/min with speech. As the breathing pattern was altered when speaking, minute volume decreased and PIAF increased.

**Table V. Summary of Minute Volume ($V_I$) and Peak Inhalation Airflow (PIAF) by Speech**

| Speech | n** | $V_I$ | | | PIAF | | |
|---|---|---|---|---|---|---|---|
| | | Mean (L/min) | Standard Deviation | Duncan Grouping* | Mean (L/min) | Standard Deviation | Duncan Grouping* |
| No | 203 | 55.3 | 20.8 | A | 169 | 53.7 | B |
| Yes | 203 | 45.0 | 18.6 | B | 266 | 69.6 | A |

* Means with the same letter are not significantly different from each other.
** n represents the number of data sets (the maximum for each category is n=245).

Significant differences in $V_I$ and PIAF for all workload were also found among the subjects (Table VI), the individual variability in $V_I$ was 34% and for PIAF 37%. The average PIAF to $V_I$ ratio (PIAF/$V_I$) was 4.4 (range=3.9–5.0). Table VII contains the data for all RPDs in order of work rates with and without speech.

**Table VI. Summary of Minute Volume ($V_I$) and Peak Inhalation Air Flow (PIAF) by Subject**

| Subject ID | n** | $V_I$ | | | PIAF | | |
|---|---|---|---|---|---|---|---|
| | | Mean (L/min) | Standard Deviation | Duncan Grouping* | Mean (L/min) | Standard Deviation | Duncan Grouping* |
| 1 | 52 | 39.6 | 13.3 | G | 175 | 47.9 | F |
| 2 | 62 | 46.1 | 16.2 | D | 231 | 91.5 | C |
| 3 | 58 | 55.8 | 17.1 | C | 227 | 59.1 | D |
| 4 | 66 | 61.3 | 26.8 | A | 240 | 75.1 | B |
| 5 | 48 | 41.0 | 12.4 | F | 190 | 57.4 | E |
| 6 | 64 | 59.7 | 22.3 | B | 269 | 93.1 | A |
| 7 | 56 | 42.5 | 14.1 | E | 170 | 49.4 | G |

* Means with the same letter are not significantly different from each other.
** n represents the number of data sets (the maximum for each subject is n=70 (35 with speech and 35 without speech)).

## DISCUSSION

As pointed out in earlier published papers, breathing resistance has a significant impact on the user. Johnson *et al*. (1999) concluded that when working at 80–85% $V_{O2\ max}$, any breathing resistance would degrade performance of a respirator user. Silverman and Billings (1961) identified that expiratory resistance produced a more marked reduction in capacity to perform external work than inspiratory resistance. They recommended that *"A limit on external respiratory work appears to be the best basis for stating **tolerable** limits of resistance, since respiratory work rate involves both flow and resistance. It would seem reasonable also to express **tolerable** limits on a basis of total external work rate".* They suggest that if the breathing resistance in this case would have been limited to 0.6% of the total external work load (135W), the overall subjective complaint of discomfort would have been lowered.

A subjective reaction was expressed by the test subjects in this test, in particular with the M40 mask. All subjects remarked that the M40 mask had a significantly higher breathing resistance than all the other masks.

There was no significant difference between the M40 and the SEASMF in regard to inhalation resistance, but there was a significant difference in the exhalation resistance. This indicates that test subjects could not identify which resistance, inhalation or exhalation resistance, was most difficult to handle. They simply responded that the respirator was hard to breathe through.

**Table VII. Summary of Minute Volume ($V_I$) and Peak Inhalation Airflow (PIAF) by Workload and Speech**

| Work Load (W) | Speech | n** | $V_I$ BTPS L/min | Standard Deviation $V_I$ | Average PIAF BTPS L/min | Standard Deviation PIAF | 95th Percentile PIAF BTPS L/min |
|---|---|---|---|---|---|---|---|
| 50 | No | 35 | 33 | 5.9 | 113 | 22.2 | 172 |
| 75 | No | 35 | 41 | 6.4 | 135 | 24.8 | 201 |
| 100 | No | 35 | 48 | 6.9 | 152 | 20.3 | 206 |
| 125 | No | 35 | 57 | 8.1 | 173 | 25.4 | 240 |
| 150 | No | 32 | 68 | 10.1 | 200 | 27.4 | 272 |
| 175 | No | 25 | 84 | 11.8 | 240 | 30.4 | 320 |
| 200 | No | 6 | 114 | 15.8 | 321 | 35.4 | 415 |
| 50 | Yes | 35 | 27 | 4.2 | 211 | 40.5 | 318 |
| 75 | Yes | 35 | 31 | 5.6 | 236 | 52.7 | 375 |
| 100 | Yes | 35 | 39 | 6.7 | 254 | 53.3 | 395 |
| 125 | Yes | 35 | 47 | 8.3 | 266 | 55.1 | 412 |
| 150 | Yes | 32 | 57 | 10.1 | 292 | 63.9 | 461 |
| 175 | Yes | 25 | 70 | 12.7 | 330 | 62.8 | 496 |
| 200 | Yes | 6 | 96 | 20.5 | 407 | 62.9 | 573 |

** n represents the number of data sets (the maximum for each workload is n=35).

We also saw a significant difference in $V_I$ between the RPDs with a large difference in exhalation resistance. The major difference between the M40 and SEASMF is the exhalation resistance (Table III) where the SEASMF RPD has an 83% lower exhalation resistance over the entire flow rate range. The inhalation resistance is not significantly different, it is within 7%. This results in 13% less volume of air breathed through the SEASMF RPD; this is likely due to the significantly lower exhalation resistance.

This test suggests that paying attention to exhalation resistance and keeping it low will reduce the overall minute volume as well as the PIAF. This in turn will extend the filter life and improve the economy, but most importantly will make the RPD more acceptable to the user. It seems to be justified that in future standards pressure-drop tests could be implemented at flow rates different from those used today, say, 100–400 L/min. This would help the respirator user to differentiate between respirators which can or cannot be worn for long consecutive periods, especially at elevated work loads.

The lowest work rate, 50 W, had an overall $V_I$ of 29.91 L/min. This corresponds well with the 30 L/min used for testing gas filters in EN:141-2000 and AS 1716. However, the average PIAF not including speech was 113 L/min, with a 95th percentile of 172 L/min at this work rate. Today we are far below this flow rate when testing RPD for pressure drop and particle filter penetration. More importantly, this is the lowest work rate and not very typical for RPD users in industry, nor in the work performed by first responders (Raven *et al.* (1979), Kaufman *et al.* (2003)).

The test flow rate of 85 – 95 L/min (pressure drop and particle penetration) has a long history. Silverman *et al*. (1943), claims that it dates as far back as the First World War (1914–1918). At that time, it was concluded that a slow run would require 42.5 L/min of air, and since it was thought that the inspiration phase is approximately 50% of the respiratory cycle, the actual flow rate of air inhaled per minute should be two times 42.5 L/min, or 85 L/min. This benchmark rate has remained unchanged. In this test inspiratory airflow rates are high for all exercises. This concurs with earlier findings by the author as well as by Kaufman and Hastings (2003), Dahlbäck and Novak (1983), Raven *et al.* (1979), Åstrand *et al*., (2003).

The findings of this study are in agreement with other authors who actually measured inhalation flow rate in preference to calculating the value. Those authors have recorded $V_I$ values of >200 L/min and PIAF values in the range of 200–550 L/min, for instance Åstrand *et al*., (2003); Dahlbäck and Novak (1983); Lafortuna *et al*. (1984); Raven *et al.* (1979); Silverman *et al*. (1943); Kaufman and Hastings (2003); Hinds and Bellin, (1987); Dunn and Winder (1996); Nunn, (1993).

When it comes to minute volume, the results presented in this paper concur with physiological research conducted since the early 1900s. However, what has only sporadically been reported in the literature is the PIAF. The reason for this is possibly that the main objective has been to gain an understanding of the motor function of humans, such as fat and carbohydrate oxidization to produce fuel for the muscles. Typically, Douglas-bags have been used to collect expired air for analysis, in order to establish the oxygen consumption for a given work rate. The focus has not been the speed of the airflows through the trachea to the lungs, as this does not affect the oxidization of fuel. As pointed out by earlier authors, airflow and pressure drop are of utmost importance when looking at the performance of respirators. If the flow is inadequate, the respirator will not protect as intended (Dahlbäck and Novak, 1983; da Roza *et al*., 1990). If the pressure drop is high it will impose undue breathing resistance on the user (Johnson *et al*., 1999), and consequently most likely will not be worn.

Descriptions and definitions of sustainable work levels can be found in data collected from various researches into physiology (Åstrand *et al*., 2003; Sharkey, 2002; Nunn, 1993; Silverman and Billings, 1961).

The heart rate (HR) during exercise, e.g. when walking, running, or cycling, increases for an average person linearly with the oxygen uptake. The relationship is not strictly on a percentage basis. When the heart rate is at 60% of maximum heart rate the oxygen uptake is approximately 42%, and at 85% of maximum heart rate the oxygen uptake is slightly below 80% of maximal aerobic power.

The test subjects' average aerobic capacity was 41.3 ± 6.8 ml/kg/min. At 125 W, their heart rate was just under 70% of their theoretical maximum. According to Åstrand *et al*. (2003) in *Textbook of Physiology*, 4th ed., p. 289, fig. 9.10, this would place them at 57–58% of $V_{O2\ max}$. According to Sharkey (2004), the subjects should be able to sustain this work rate for 40 minutes to 6 hours (depending on fitness level). Their average $V_I$ was 53.8 L/min at this work rate (57–58% of $V_{O2\ max}$), which is consistent with Sharkey's data (2004), i.e., the $V_I$ is 55 L/min at 60% of $V_{O2\ max}$.

The whole group of test subjects had an average calculated $V_{O2\ max}$ of 3.16 ±0.4 L/min (Table I). According to Åstrand *et al*. (2003) in *Textbook of Physiology*, 4th ed., p. 506, fig.3, this should give them aerobic capacity to produce external work of 200 W not wearing respirators. Two of the subjects could attain this work rate with two masks. All subjects could work at 150 W with most mask and six subjects could work at 175 W with some masks. The conclusion of this is in line with findings of physiological research (Sharkey, 2004; Myer *et al*., 1997): that a number of factors influence the ability to work with a RPD. Those factors include work rate, breathing resistance, environmental conditions (temperature, humidity, and altitude), duration, and determination (attitude to wearing a RPD). The personal aerobic fitness ($V_{O2\ max}$) and the capability to sustain aerobic capacity would be the most important parameters for people to sustain a work rate.

# CONCLUSIONS

There are significant differences in both tidal volume $V_I$ and PIAF, depending on the work rate, the subject, the presence or absence of speech, and the characteristics of the respirator. These differences are so significant to the performance of a respirator that we perhaps need to consider some changes to how we test respirators, filters and gas/vapor ad/absorbers.


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