

Inhalation Flow Rates During Strenuous Exercise

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ABSTRACT

It would be helpful if peak inhalation flow rates were characterized for respiratory design, testing, and use. However, peak flow rates depend strongly on the wearer and the type of work being performed. Instantaneous inhalation rates for subjects exercising on a treadmill have been measured for the following conditions: 1) at 80-85% $\dot{V}O_2$ max without a respirator, 2) at 80-85% $\dot{V}O_2$ max while wearing a breath-responsive PAPR (blower flow rate) and 3) at 100% $\dot{V}O_2$ max without a respirator. Instantaneous inhalation flow rates were found to vary greatly among subjects and at different times for each subject. Depending upon the time that any given flow rate can be sustained, peak flow rates can vary considerably. Instantaneous flow rates were recorded and classified according to 20 L/min ranges so that the flow rate distribution could be obtained. If flow rates in the top one percentile are defined as peak flow rates, then a peak inhalation flow rate of up to 359 L/min (BTPS) was measured for condition 1. Peak instantaneous (less than 1% of flow rates) recorded flows were even higher, up to 442 L/min (BTPS). A peak blower flow rate of up to 679 L/min (BTPS) was measured for condition 2. Flow rates recorded at 100% $\dot{V}O_2$ max were generally higher than flow rates 80-85% $\dot{V}O_2$ max, although this varied somewhat among subjects. A linear relationship has been found between peak flow rate and average minute volume, which can then be used in a procedure to calculate peak flow rates expected at any given work rate.

Keywords: peak inhalation flow rates, oxygen consumption, and respirators

INTRODUCTION

Wave shapes for flow rates of working humans are different from the sinusoids seen during inhalation at rest. If inhalation flow rate was sinusoidally-shaped, then there would be an easily definable relationship between average and peak flow. The pattern of flow rate is, instead, nearly trapezoidal, with a peak often occurring near the beginning or the end of the wave (Johnson, 1991; Johnson, 1993). The peak flow rate relationship varies among people and among breaths from the same person. Thus, the peak flow is not easily calculated from average flow rate.

Peak inhalation flow rates should be known for a number of reasons. First, flow rates supplied by powered-air purifying respirators (PAPRs) must be adequate to protect wearers (although flow rates alone do not guarantee protection). Especially for loose-fitting PAPRs, it is necessary to provide sufficient air to prevent breathing contaminated air. Face seal leakage for tight-fitting PAPRs is of concern when breathing flow rate exceeds blower flow rate and pressure inside the facepiece becomes negative. Leakage is especially of concern when beard stubble appears on the face of the wearer (deRoza et. al.,

1986). Second, respirator filters are tested with defined flow rates. Filter break-through times, capacities, and pressure drops all depend on flow rates and flow patterns. Third, non-powered air-purifying respirators (APRs) affect both the pattern of breathing (Silverman et. al., 1951) and the average flow rate of breathing (Johnson, et. al., 1999). Fourth, many APRs incorporate the use of nose cups to minimize respirator dead volumes and reduce lens fogging. Nose cups feel uncomfortable to many wearers (Carette, 2003), and interfere with nose breathing of others. The need for nose cups depends in part on flow rates encountered inside the facepiece. Fifth, peak flow rates and breathing patterns may be incorporated into various respirator standards (ISO), and thus can have legal standing for certification requirements. It is important that these standards reflect the best possible scientific data available at the time.

In order to minimize possible respiratory effects of respirators, one must know how much degradation is caused by the respirator. That requires knowing the unencumbered response.

METHODS

This study was performed in three distinct parts. These were:

- 1) Flow rates measured at 80-85% $\dot{V}O_2$ max without wearing a respirator,
- 2) Flow rates measured at 80-85% $\dot{V}O_2$ max while wearing an SE-400 breath-responsive PAPR (SEA, Branford, CT).
- 3) Flow rates measured at the conclusion of $\dot{V}O_2$ max tests without wearing a respirator,

The numbers of subjects participating in each of these parts differed and appear in Table I. The PAPR comparison groups appearing in Table I are those subjects who participated in both parts 1) and 2) of this study. All testing protocols were approved by the University of Maryland Institutional Review Board.

Table I. Participant Characteristics

Demographic	80-85% $\dot{V}O_2$ max no respirator	80-85% $\dot{V}O_2$ max PAPR	80-85% $\dot{V}O_2$ max (PAPR Comparison)	100% $\dot{V}O_2$ max no respirator
Number (Sexes)	24 (14M, 10F)	13 (6M, 7F)	10 (5M, 5F)	9 (4M, 5F)
Age (years)	23.3 ± 4.6 (19-35)	24.1 ± 5.9 (19-35)	24.6 ± 5.9 (19-35)	23.3 ± 2.8 (19-28)
Mass (kg)	67.1 ± 10.1 (44-91)	67.1 ± 12.4 (591)	67.7 ± 12.9 (54-91)	66.0 ± 9.1 (49-74)
Height (cm)	171 ± 8.6 (160-183)	169 ± 9.0 (157-183)	169 ± 9.4 (160-183)	172 ± 7.6 (163-183)
$\dot{V}O_2$ max (L/min)	2.7 ± 0.7 (1.5 – 4.3)	2.9 ± 0.8 (1.5 – 4.3)	2.9 ± 0.9 (1.5 – 4.3)	2.4 ± 0.6 (1.5 – 3.5)
HR max (b/min)	195 ± 11.1 (168-211)	193.4 ± 9.9 (168-203)	194 ± 10.4 (168-203)	197 ± 13.8 (186-211)
Trait Anxiety (STAI)	33.4 ± 9.5 (20-52)	35.5 ± 10.2 (25-52)	33.9 ± 9.3 (25-52)	32.2 ± 10.7 (20-52)

Note: Values given are means ± standard deviation. Ranges are given in parentheses.

Orientation

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 Readiness Questionnaire (PAR-Q) (BCMH, 1978; Thomas et al., 1992) were both used to determine whether vigorous activity was appropriate.

Subjects selected for this study were a mix of paid and unpaid volunteers who gave written consent for their participation. A Spielberger State-Trait Anxiety Inventory (STAI) Test (Spielberger et al., 1970) was given to all volunteers to measure their anxiety levels, known to influence responses to respirator use (Johnson et al., 1995). The STAI test consists of a series of written multiple choice questions for which the respondent assesses her/his feelings. Test scores less than 30-35 are considered to be nonanxious; those above reflect higher levels of anxiety.

Calibration

All equipment was carefully calibrated before each test. Flow rates were calibrated by first determining any zero offsets in the system. With no flow applied, the output signal from the data acquisition system was accumulated for 30 seconds and then divided by this time to obtain an average zero offset value. The mean offset was then subtracted from subsequent readings. A three liter syringe was discharged through the pneumotach in five seconds or less, and the output signal accumulated to give a value corresponding to the syringes volume. A calibration factor was automatically calculated to give pneumotach flow rate. Because pressures were not measured, no pressure calibration was necessary for these tests.

The pneumotach has been checked periodically for a linear flow-pressure characteristic, and has been found to be linear. Thus, calibration at one flow rate is all that is needed to measure a range of flow rates.

The mass spectrometer was calibrated with test gases of known composition (4% CO₂, 16% O₂). This calibration was performed at daily intervals. A quick check of atmospheric gas concentrations was also performed daily.

Flow rates with the SE-400 breathing-responsive PAPR were measured with a custom flow measuring system provided by the manufacturer. The flow-sensing portion of this system was incorporated within the respirator and was not directly accessible to laboratory personnel. The system had been calibrated by the manufacturer within a few months of this use.

Maximum Oxygen Consumption Pre-Test

A maximal oxygen consumption test was performed on all prospective participants using a Quinton (Bothell, WA) motorized treadmill. Participants were asked to warm-up and stretch for approximately 5-10 minutes prior to the start of the test. After the warm-up the participants breathed through a Hans Rudolph (Kansas City, MO) two-way breathing valve configured with a rubber adaptable mouthpiece. This apparatus was interfaced with a standard Fleisch #4 (Phipps and Bird; Richmond, VA) pneumotach, with a linear range up to at least 800 L/min, and Perkin Elmer (St. Louis, MO) Model 1100 mass spectrometer to monitor continuous expired airflow and oxygen consumption. Heart rate measurement was assessed using a standard ECG 3-lead electrode configuration with the leads connected to a Hewlett Packard (Siemens; Andover, MA) Patient Monitoring System. The initial work rate was established at a speed and grade designed to elicit 70% of the participant's age-predicted maximal heart rate. The work rate (speed and grade) was adjusted every third minute until the participant experienced volitional fatigue, failed to display a rise in oxygen consumption (150 mL O₂ per minute) in accordance with the increase in work rate, or exhibited cardiovascular responses that contraindicated further assessment. Most subjects completed the $\dot{V}O_2$ max test in about 9-15 minutes.

80-85% $\dot{V}O_2$ max Testing, No Respirator

Sessions were conducted at 80-85% of the participant's maximal aerobic capacity using the motorized treadmill. One session utilized the Hans-Rudolph two-way breathing valve configured with a rubber

adaptable mouthpiece and attached to a Fleisch #4 pneumotach (with an extremely low $0.1 \text{ cm}^3 \text{ H}_2\text{O} \cdot \text{sec/L}$ pneumotach (only) resistance) to measure inspiratory flow rates. The data were logged at 50 Hz using a DAS-8 (Metrabyte-Krithley; Tawnton, MA) 12 bit analog-to-digital converter board installed in a PC, Validyne (Northridge, CA) DP15 differential pressure transducer, and custom software developed specifically for our laboratory (Johnson and Dooly, 1994).

Each participant was asked to warm-up and stretch for approximately 5-10 minutes prior to the start of the session. The treadmill speed and grade were set at a work rate eliciting approximately 70% of the individual's age-predicted maximal heart rate, as determined from the $\dot{V}O_2$ max test. This work rate was slowly increased to the predetermined speed and grade corresponding to 80-85% of the participant's maximal aerobic capacity. The participant was then asked to exercise at this intensity for 6 minutes. Flow rate data were used for the entire last three minutes of each of the 80-85% $\dot{V}O_2$ max tests, when steady-state was reached. All test sessions, including the $\dot{V}O_2$ max test, included a five-minute cool down period of walking on the treadmill.

80-85% $\dot{V}O_2$ max Testing, Breath Responsive PAPR

Testing was conducted similarly to the 80-85% $\dot{V}O_2$ max sessions with no respirator except that subjects wore an SE-400 (SEA; Branford, CT) breath responsive tight-fitting full-facepiece PAPR. Flow rate data were collected using a custom-built SEA data acquisition system at a rate of 50Hz. Flow rates were measured downstream from the PAPR blower and utilized a combination of pressure drops across the filter and inhalation valve. The system had been calibrated by the manufacturer within 6 months of this test. It was not practical to calibrate the system in our laboratory. This system measured air supplied to the PAPR facepiece, and flow rates were expected to be somewhat higher than subject inspiratory flow rates. Subjects walked for 6 minutes, with the last 3 minutes of data, assumed to be at steady-state, analyzed for instantaneous flow rates.

100% $\dot{V}O_2$ max Test

For a subset of all the subjects who underwent $\dot{V}O_2$ max testing, inhalation flow rates were recorded during the final 30 seconds of the test. Inhalation and exhalation flows were separated using a Hans-Rudolph one-way breathing valve. Inhalation flows were measured with a Fleisch #4 pneumotach and Validyne DP-15 differential pressure transducer system. Data were logged into a computer at a rate of 50 Hz.

Data Analysis

Inhalation flow rates were obtained through a Hans-Rudolph two-way valve that should separate inhalation from exhalation flows. It was noticed, however, that data indicated some exhalation flows were being recorded (Figure 1a). These findings could be due to either: 1) a leaky valve allowing exhalation flow to pass through the pneumotach on the inhalation side of the valve, or 2) an uncompensated zero offset in the measurement system. Peak inhalation flows for the first instance would be correct as they stood, but peak inhalation flow rates would have to be corrected for the zero offset if the second were true.

To determine the cause of the problem, several volunteer subjects from our laboratory were asked to walk on the treadmill with two flow measurement conditions: 1) the two-way valve in place in the breathing circuit and the pneumotach configured to measure only inhalation flow rates and 2) no valve was used; only hoses conducted air from the mouth to the pneumotach. Results from one of these tests can be seen in Figure 2. Peak flow rates for the exercising subject gradually increased with time during the periods when the valve was not in place. This was interpreted as a response to the dead volume present in the tubing. Without an exhalation valve to separate expired air from inspired air, exhaled carbon dioxide was recycled into inspired air and this stimulated deeper breathing in the subject.

Because this gradually increasing flow rate behavior was not seen in recordings of flow rates for the periods when breathing through the two-way valve, nor for the other subjects performing the main part of this study, it was concluded that the problem was a zero offset that needed to be corrected.

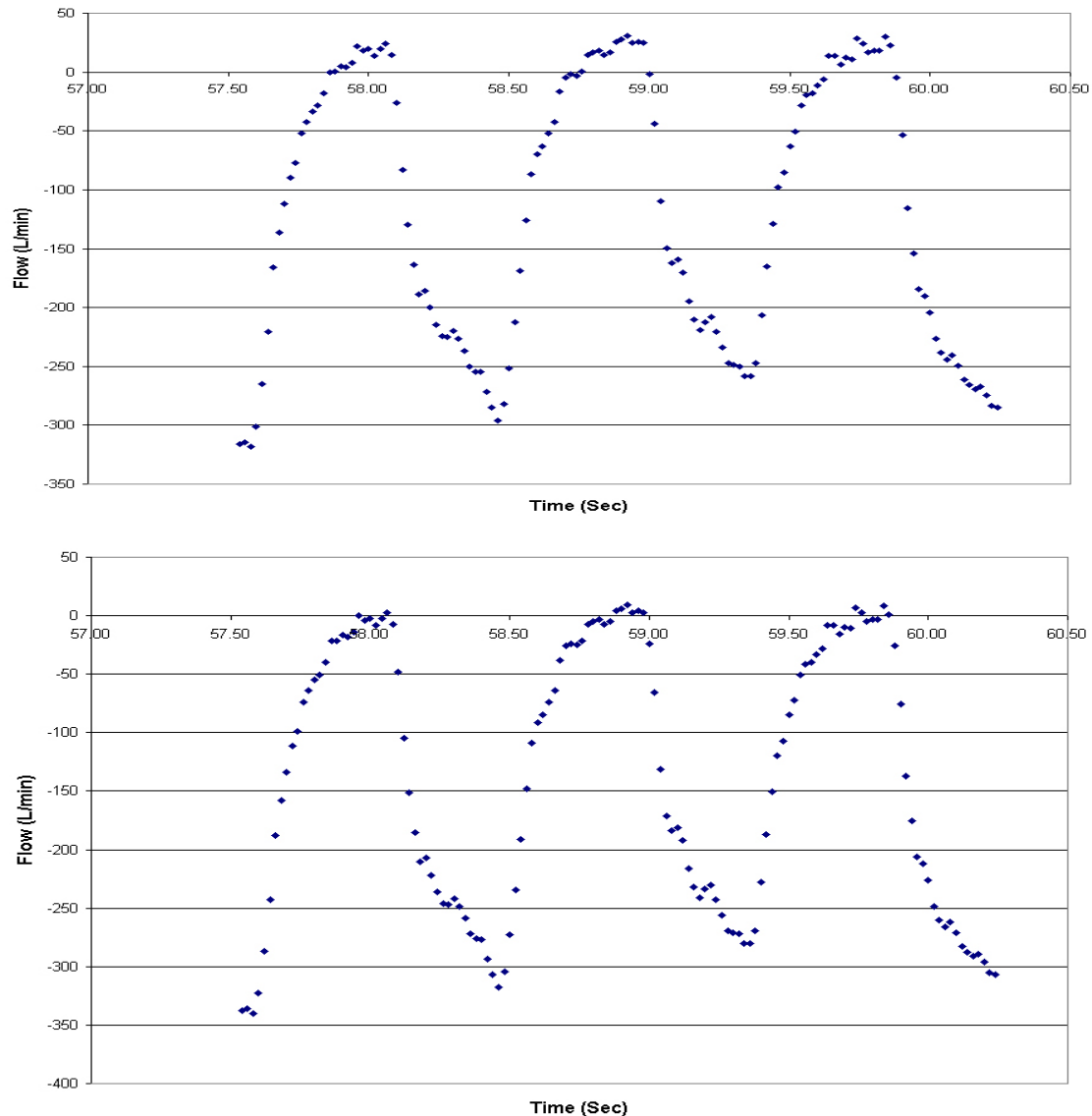


Figure 1. Inhalation flow rate waveflows a) before offset correction, and b) after offset correction. Inhalation flow rates are given as negative values.

Data were subjected to an automated procedure to estimate the correct zero value. On rare occasions the offset had to be determined by viewing the waveform. In this case, exponential smoothing (Bloch, 2003) was used to reduce noise in the data to make a better estimate of the offset that required correction. As shown in Figure 1 a & b, flow rate data were able to be corrected for the apparent offset, and instantaneous flow rates could then be measured. Peak flows were identified as the flow rate that appeared in each data record. Alongside the flow rate values for 80-85% $\dot{V}O_2$ max are given flow rates

for the same subjects exercising at 100% $\dot{V}O_2$ max. Flow rates at 100% $\dot{V}O_2$ max are greater than those at 80-85% $\dot{V}O_2$ max. Data from the SEA flow measuring system were analyzed and displayed with custom software supplied by the manufacturer. No further adjustments were made to these data.

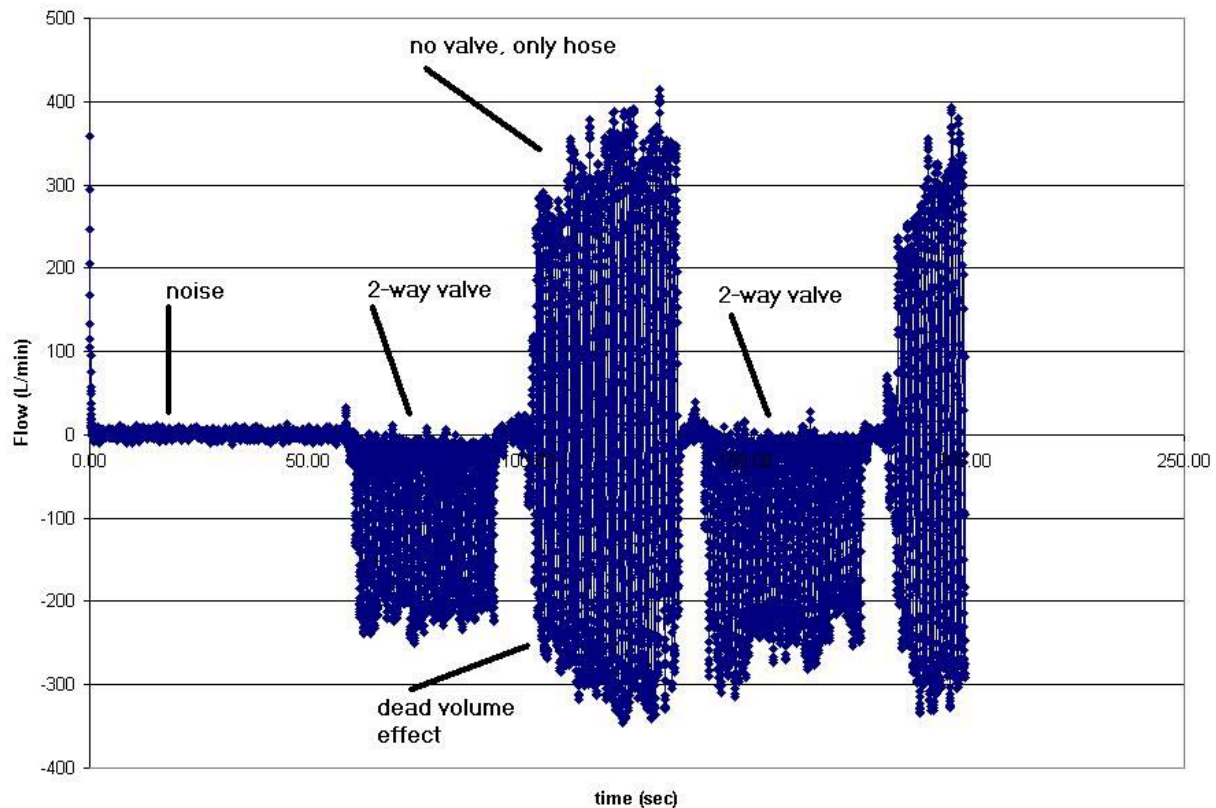


Figure 2. Flow rate tracings to test for the cause of the offset. During periods with the two-way valve in place, only inhalation flow rates were measured. With the valve replaced by a hose, exhalation flow rate was measured in addition to inhalation flow rate. The larger inhalation flow rates measured without the two-way valve were attributed to CO_2 stimulation of breathing. Inhalation flow rates are given as negative values.

There was no selection procedure used to separate certain flow rate data from others. All instantaneous flow rates were converted into BTPS (Body, Temperature, Standard Pressure, Saturated with Water Vapor) conditions in order to standardize them. Otherwise, inhalation data could vary with ambient conditions. All flow rate data were separated into various ranges with a computer program. The number of instances that certain breathing flow rates were present in each range was accumulated and converted into a percentage of all flow rates. Data were pooled for all subjects.

RESULTS

Flow rate ranges at 80-85% $\dot{V}O_2$ max are given in Figure 3. In this figure are shown the percentages of flow rates that fall into the 20 L/min flow rate range appearing on the abscissa (horizontal axis) of the graph.

The flow waveshape cannot be reproduced from the data appearing in Figure 3. To illustrate this point, Figure 4 is a composite of a graph of typical flow rate data with time at the top and the corresponding flow rate ranges at the bottom for the section of data illustrated above in Figure 4. The bottom graph of flow rate ranges is given in terms of percentages in each range.

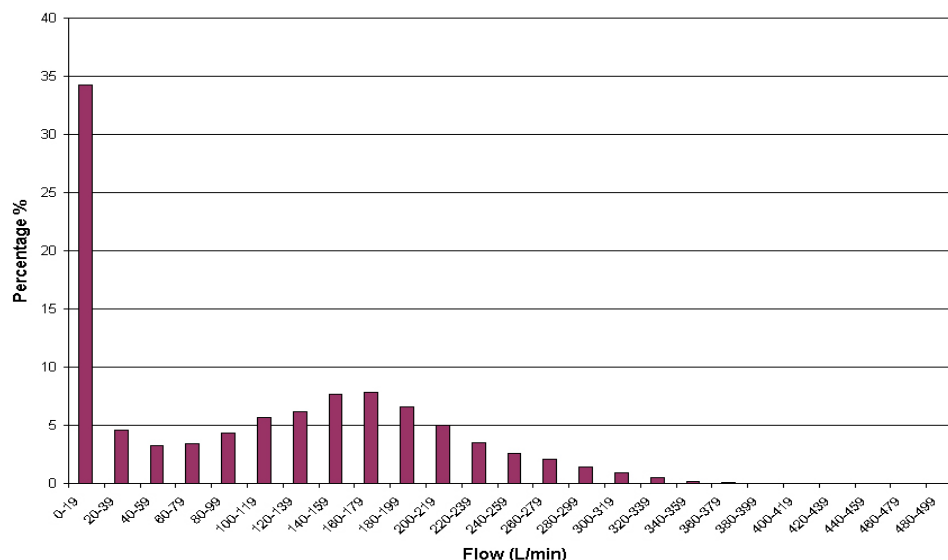


Figure 3. Flow rate percentages exhibited by 24 subjects working at 80-85% $\dot{V}O_2$ max without wearing a respirator. A flow rate in the range of 360-379 L/min is discernable from the graph.

Peak flow rates vary with time for any given subject and also vary among subjects. In an attempt to assess the importance of occurrence of any particular flow rate, Table II lists the percentages of the total number of tested subjects who exceeded flow rates in the given ranges for three different percentages of occurrence. For instance, 13% of the subjects exhibited 300-319 L/min 3% of the time. If it is deemed important to supply enough air to the hardest-breathing 13% of the subject population, then a blower must supply at least 319 L/min 3% of the time. This information allows the assessment of the importance of supplying air at any particular flow rate.

In Figure 5 are shown flow rate data for 10 subjects wearing the breath-responsive PAPR, and, for comparison purposes, data for the same subjects not wearing the PAPR. It can clearly be seen that measured flow rates while wearing the PAPR were consistently higher than data from unencumbered subjects. The likely reason for this is that the PAPR supplied excess air to the facepiece in order to maintain positive facepiece pressure and guard against inward leakage. Flow rates measured represent blower flow rather than respiratory flow. In order to protect the wearer of this PAPR for the same length of time as an air-purifying respirator (APR), the filter used with this PAPR must have a larger capacity than the APR filter to account for the additional accumulated flow.

This PAPR incorporated a pressure transducer and audio signal should pressure become negative. The audio alarm did not sound for most subjects; thus, positive pressure inside the facepiece was indicated. For subjects with very high peak flow rates (e.g., subject #145), the alarm sounded often, indicating that the blower could not adjust rapidly enough to peak flows.

In Table III are shown percentages of the entire subject population of 13 whose flow rates exhibit certain values for three different percentages of time while wearing the PAPR. Table III reflects what is conveyed in Figure 5; higher flow rates must be supplied by the blower in order to maintain positive pressure inside the facepiece for a certain percentage of the population for a given percentage of the time.

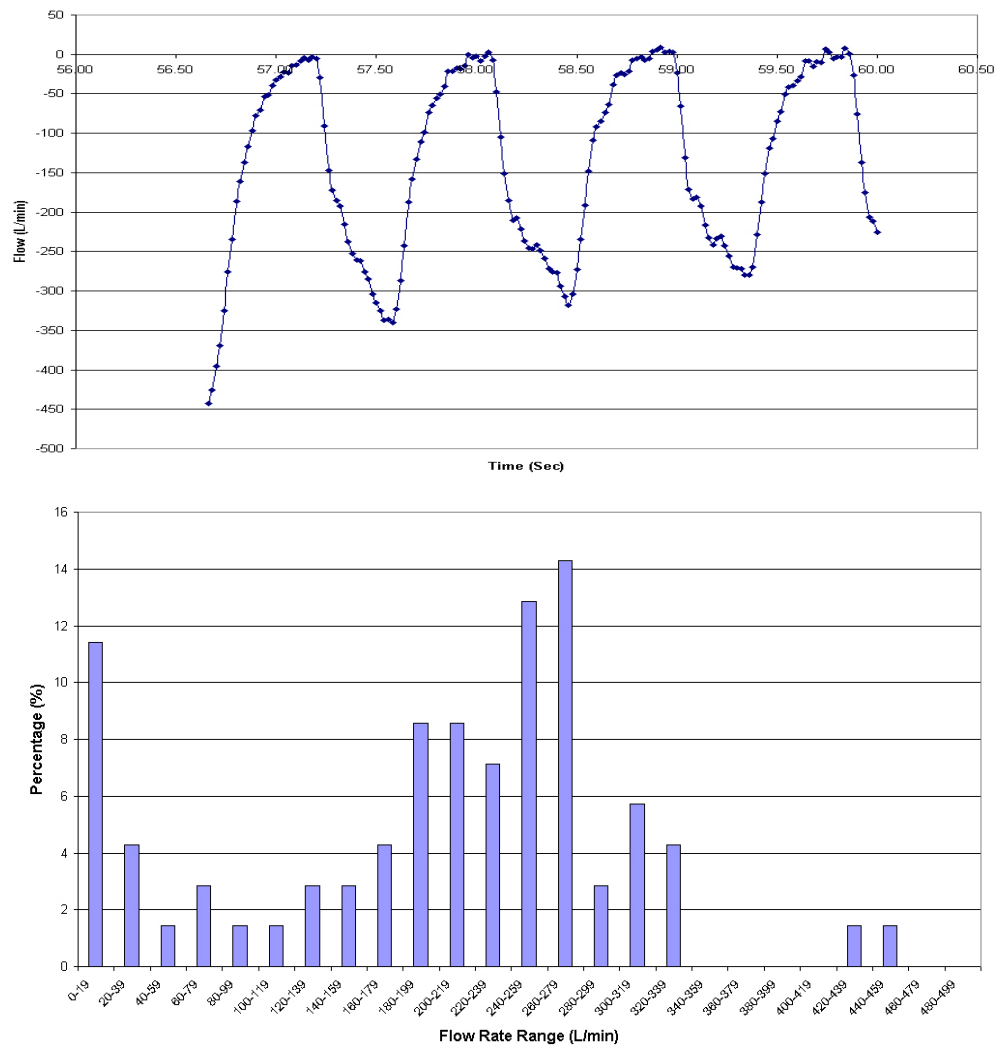


Figure 4. Composite of flow rate with time as measured on one subject (a) contrasted with the percentage of flow rates in range groups (b). The flow waveform cannot be inferred from the percentages of flows.

Table II. Percentages of 23 Subjects Who Exhibited Indicated Flow Rate Ranges (80-85% $\dot{V}O_2$ max, no respirator condition)

Flow Rate L/min BTPS	Percentage of the Time		
	5%	3%	1%
0-19	100.0	100.0	100.0
20-39	100.0	100.0	100.0
40-59	100.0	100.0	100.0
60-79	100.0	100.0	100.0
80-99	100.0	100.0	100.0
100-119	100.0	100.0	100.0
120-139	100.0	100.0	100.0
140-159	91.3	91.3	95.7
160-179	87.0	87.0	91.3
180-199	69.6	78.3	82.6
200-219	60.9	65.2	69.6
220-239	34.8	39.1	52.2
240-259	26.1	34.8	34.8
260-279	17.4	21.7	26.1
280-299	13.0	17.4	17.4
300-319	13.0	13.0	13.0
320-339	8.7	13.0	13.0
340-359	0.0	4.3	13.0
360-379	0.0	0.0	4.3
380-389	0.0	0.0	0.0

In Figure 6 are shown data for 9 subjects tested at 100% $\dot{V}O_2$ max. For comparison purposes, data for the same subjects exercising at 80-85% $\dot{V}O_2$ max without a respirator are given as well. It can be seen that flow rates for 100% $\dot{V}O_2$ max exceed flow rates for 80-85% $\dot{V}O_2$ max. Table IV depicts the same information by percentage of the population and by time of occurrence. Alongside flow rate values for 80-85% $\dot{V}O_2$ max are given flow rates for the same subjects exercising at 100% $\dot{V}O_2$ max. Flow rates at 100% $\dot{V}O_2$ max are greater than those at 80-85% $\dot{V}O_2$ max.

The relationship between peak flows (obtained from a breath-by-breath analysis of each data set) and average minute volume is given in Figure 7 for subjects exercising on a treadmill at 80-85% $\dot{V}O_2$ max and 100% $\dot{V}O_2$ max. Peak inhalation flow rate can be seen to be linearly related to average minute volume given for BTPS conditions. Even a casual glance at the flow rates in Figure 7 will be enough to notice that they are higher than the values that appear in the Tables. That is because the flow rate values in the Figure are instantaneous peak flow rates that did not persist for even 1% of the time. The difference demonstrates that peak flow rates do not usually persist for very long.

Table III. Percentages of 13 Subjects Who Exhibited Indicated Blower Flow Rate Ranges (Breath-Responsive demand PAPR condition 80-85% $\dot{V}O_2$ max)

Flow Rate L/min BTPS	Percentage of the Time		
	5%	3%	1%
0-19	100.0	100.0	100.0
20-39	100.0	100.0	100.0
40-59	100.0	100.0	100.0
60-79	100.0	100.0	100.0
80-99	100.0	100.0	100.0
100-119	100.0	100.0	100.0
120-139	100.0	100.0	100.0
140-159	100.0	100.0	100.0
160-179	100.0	100.0	100.0
180-199	100.0	100.0	100.0
200-219	100.0	100.0	100.0
220-239	100.0	100.0	100.0
240-259	92.3	100.0	100.0
260-279	92.3	92.3	92.3
280-299	46.2	69.2	76.9
300-319	38.5	38.5	46.2
320-339	38.5	38.5	38.5
340-359	38.5	38.5	38.5
360-379	15.4	30.8	38.5
380-399	15.4	15.4	30.8
400-419	15.4	15.4	15.4
420-439	7.7	15.4	15.4
440-459	7.7	7.7	15.4
460-479	7.7	7.7	7.7
480-499	7.7	7.7	7.7
500-519	7.7	7.7	7.7
520-539	7.7	7.7	7.7
540-559	7.7	7.7	7.7
560-579	7.7	7.7	7.7
580-599	7.7	7.7	7.7
600-619	0.0	7.7	7.7
620-639	0.0	7.7	7.7
640-659	0.0	0.0	7.7
660-679	0.0	0.0	7.7
680-699	0.0	0.0	0.0
700-719	0.0	0.0	0.0
720-739	0.0	0.0	0.0

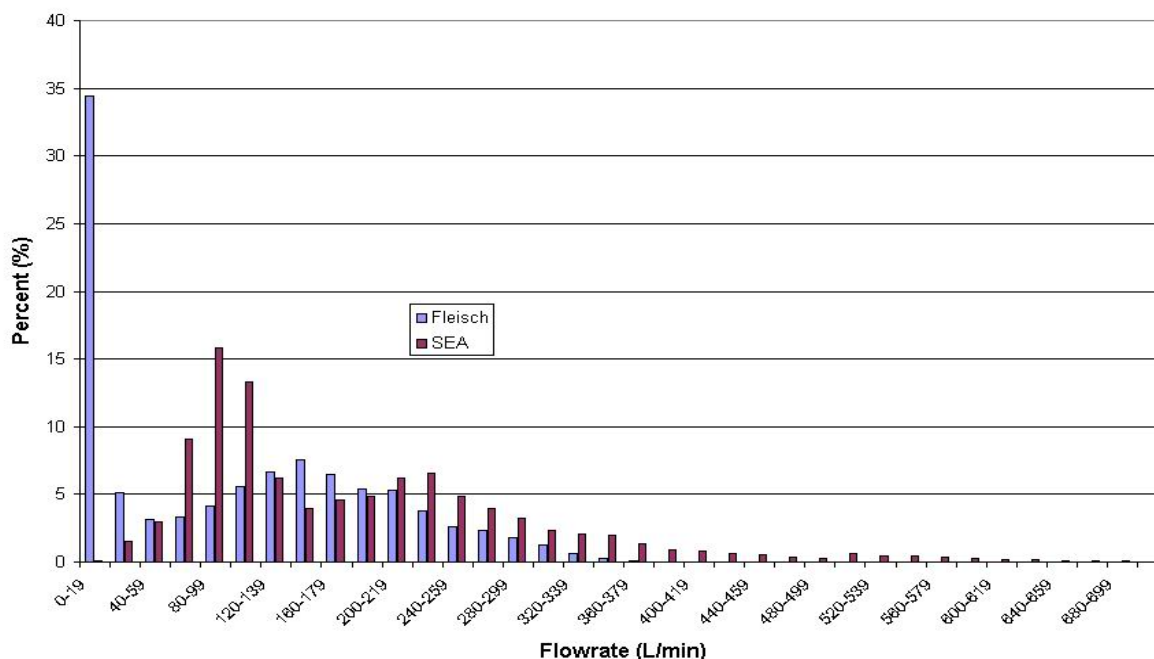


Figure 5. Flow rate percentages for ten subjects wearing the SE-400 breathing demand PAPR (darker bars) compared to data from the same ten subjects without wearing a respirator (lighter bars). Flow rates are higher with the PAPR.

DISCUSSION

The data that have been measured here point out one important fact: different people generate different flow rates. There are those whose peak flows are not nearly as great as the peak flows of others. This is inter-subject variability. For the data reported here, the average peak flow, as determined from a breath-by-breath scrutiny of the data, is 215 L/min with an average maximum of 269 L/min and a standard deviation of 26.5 L/min (Table V). On the other hand, each subject breathed with a range of flow rates to give a flow rate distribution. This is intra-subject variability. Each subject exhibited a different mean, maximum, and standard deviation, again found in Table V. These standard deviations may be somewhat inflated because local peaks were sometimes included as peak flows.

The trick is to combine intra-subject and inter-subject variability in a way that has meaning for the entire population. The difficulty here is that values given may be much too high for the slight breathers and underestimated too much for the heavy breathers. We have attempted to face this difficulty in the way data are presented in this paper.

The values of peak flow rates can be of interest for a number of reasons, mostly discussed earlier. Although flow rates are only one contributor to respiratory protection, they can be important nevertheless. What is often overlooked, however, is their potential contribution to the subjective feeling of the respirator wearer. Feelings of anxiety and dyspnea that some wearers experience in a respirator may have something to do with breathing patterns that do not feel right because they are confined by the respirator. Over the course of a lifetime, one can become used to a certain feel of breathing: muscle tensions, blood oxygen saturation, and carbon dioxide levels are all part of a normal pattern of breathing. Change these slowly, and adjustments come easily; change these abruptly, and some sensitive people may feel uncomfortable. It is unknown at this point whether such mechanisms operate, and if they do, the

degree to which a small change, such as a muscle contraction that does not result in additional flow, can contribute to a feeling of breathlessness. It had been speculated years ago (Johnson, 1991) that muscle “length-tension inappropriateness” is a contributor to dyspnea. Perhaps we will find out that the same mechanism is important for certain respirator wearers.

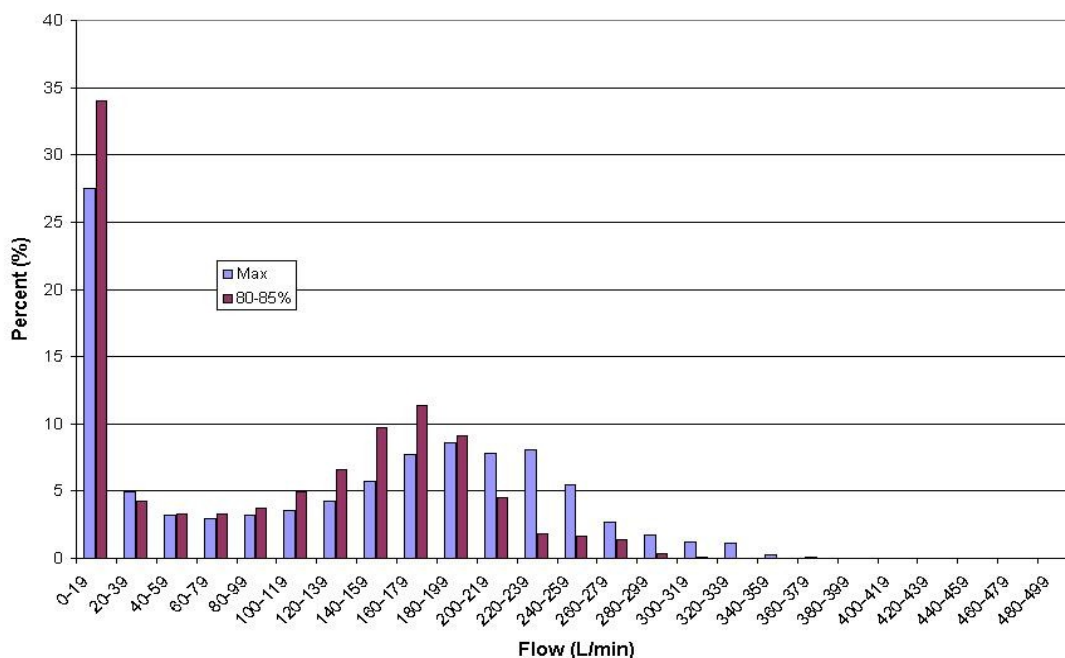


Figure 6. Flow rate percentages for nine subjects at 100% $\dot{V}O_2$ max when not wearing a respirator (light bars). For comparison, data from the same subjects at 80-85% $\dot{V}O_2$ max are plotted as well (darker bars). Flow rates at 100% $\dot{V}O_2$ max exceed flow rates at 80-85% $\dot{V}O_2$ max.

Although flow rate data have been recorded for many years, measurement technology has changed significantly since the middle of the twentieth century. In addition, the physical stature of workers and potential subjects has also changed in that time. Subject pools are today much more diverse, including representation from women and a mixture of races that would have been unusual fifty years ago. Hence, we are hesitant to make direct comparisons between published reports from that time and from this paper. Two studies of peak flow rates have recently been published, however. Berndtsson (2004) reported on peak inspiratory flow rates for seven subjects exercising at work rates ranging from 50 to 200 W, wearing six different types of respiratory protective devices, and either speaking or not speaking. At the highest workload of 200 W, (corresponding to about 90% $\dot{V}O_2$ max for his subjects), the average peak inhalation flow rate obtained from his Table VII (without speech) was 321 L/min BTPS, which was comparable to the value in this study of 359 L/min at 80-85% $\dot{V}O_2$ max (Table II, 4% of subjects (1 subject) exceeding 359 L/min 1% of the time). Values in this report might be expected to be somewhat higher than values obtained by Berndtsson because his values were obtained from subjects wearing various respirators with their accompanying filters, whereas data in this study were obtained from subjects unencumbered by respirators. Inhalation and exhalation resistances have been shown to reduce minute volumes (Johnson et al., 1999; Caretti et al., 2001), despite the statement by Berndtsson that reduction of exhalation resistance should lower respiratory minute volume.

Table IV. Percentages of 9 Subjects Who Exhibited Indicated Inhaled Flow Rate Range: Comparing 80-85% $\dot{V}O_2$ max and 100% $\dot{V}O_2$ max, no respirator condition

Flow Rate L/min BTPS	100% $\dot{V}O_2$ max			80-85% $\dot{V}O_2$ max		
	Percentage of the Time			Percentage of the Time		
	5%	3%	1%	5%	3%	1%
0-19	100.0	100.0	100.0	100.0	100.0	100.0
20-39	100.0	100.0	100.0	100.0	100.0	100.0
40-59	100.0	100.0	100.0	100.0	100.0	100.0
60-79	100.0	100.0	100.0	100.0	100.0	100.0
80-99	100.0	100.0	100.0	100.0	100.0	100.0
100-119	100.0	100.0	100.0	100.0	100.0	100.0
120-139	100.0	100.0	100.0	100.0	100.0	100.0
140-159	100.0	100.0	100.0	88.9	88.9	100.0
160-179	100.0	100.0	100.0	88.9	88.9	88.9
180-199	100.0	100.0	100.0	66.7	77.8	77.7
200-219	66.7	77.8	100.0	55.6	55.6	77.8
220-239	66.7	66.7	66.7	11.0	11.1	66.7
240-259	55.6	55.6	66.7	11.0	11.1	44.4
260-279	33.3	44.4	44.4	11.0	11.0	11.0
280-299	11.1	11.1	22.2	0.0	11.0	11.0
300-319	11.1	11.1	11.1	0.0	0.0	0.0
320-339	11.1	11.1	11.1	0.0	0.0	0.0
340-359	0.0	0.0	11.1	0.0	0.0	0.0
360-379	0.0	0.0	0.0	0.0	0.0	0.0

Also, it was not stated in the Berndtsson (2004) paper how or where air flow rate measurements were made. A resistance flow measuring device was used. If flow rates were sampled digitally, as would be expected, then the rate of sampling could influence reported results because peak flows typically exist for short durations. If all respirators used in Berndtsson's study were full-facepiece air-purifying respirators, and respirators used were identified only by manufacturer and model number, then the placement of the flow meter would be much less critical than if a PAPR were used. This can be seen in Figure 5 of this paper, where flow rates measured in the path downstream from the blower in the SE-400 breath-responsive PAPR are higher than flow rates measured from subjects not wearing respirators. The difference is that, in order to maintain positive pressure inside the facepiece, some extra flow must be provided in addition to that supplied to the wearer. The SE-400 is a very sophisticated device that would probably provide the highest levels of protection needed in certain critical situations, but the additional flow rate provided by the blower would be expected to shorten the useful filter life by some small amount.

The second report cited for comparison is by Kaufman and Hastings (2003). Forty-eight U.S. Marines performed nine different operationally-relevant physical tasks, each with a duration between 30 and 200 sec. Flow rates were measured with a turbine flow meter in series with the respirator filter and sampled at a rate of 50 Hz. Peak flow rates were selected from periods of maximum respiratory flow. They reported an average peak inspiratory flow rate of 239 L/min during testing, although the average peak flow rate capability of their subjects (measured during pulmonary function testing) was 365 L/min.

The average peak flow of 239 L/min reported by Kaufman and Hastings was considerably below the 321 L/min reported by Berndtsson and the 359 L/min reported in the present study. Conditions of the Kaufman and Hastings test were much different from the two comparison tests. First, the Kaufman and Hastings test work rate conditions were not held steady as in the other two tests. Respiratory responses usually take at least three minutes to reach steady-state, so the short periods of transition from one of their tasks to another would likely have reduced peak inspiratory flows. Second, Kaufman and Hastings

used a turbine flow meter with its inherent inertia. Although they did correct for inertial effects around zero flow, it is likely that some peak flows, as quick as they are, were not detected. Third, subjects used by Kaufman and Hastings were heavier and physically more fit than subjects in the other two studies. Berndtsson reported an estimate of $\dot{V}O_2$ max for his subjects of 3.2 L/min and average mass of 78.0 kg; Kaufman and Hastings (correcting for an error in units in their Table III) reported an average $\dot{V}O_2$ max of 3.9 L/min (estimated from a submaximal step test) and average mass of 80.3 kg. Subjects in this study had values averaging 2.4 to 2.9 L/min and masses of 67-75 kg (Table I). More physically fit subjects usually have better ventilation efficiency than less physically fit subjects, so peak inhalation flow rates, although perhaps applicable to U.S. Marines performing operational tasks, may not be quite as representative of responses of the average worker. Lastly, the forty-eight subjects tested by Kaufman and Hastings, because of the relatively large number, could possibly be more representative of the population from which they were drawn than the seven subjects tested by Berndtsson and the various numbers of subjects tested in this study.

Table V. Peak Flow Statistics for Each Subject Based on a Breath-By-Breath Analysis

Subject	Mean (L/min)	Std. Dev. (L/min)	Max (L/min)
145	306	44.5	442
223	185	22.4	228
265	149	17.8	197
290	190	23.7	247
292	202	27.6	269
302	140	16.8	171
304	312	34.8	383
306	260	30.7	313
325	235	27.2	276
328	199	23.8	253
329	177	20.6	207
330	121	14.7	151
340	241	30.9	293
344	151	18.6	179
351	122	15.2	192
353	238	29.3	281
358	255	33.8	310
365	271	30.9	318
366	236	29.7	293
376	201	26.3	302
380	207	24.3	241
381	189	24.4	231
382	248	30.5	248
average	215	26.5	269

Caretti (2003B) showed a linear relationship between peak inhalation flow rates and average minute volumes for data appearing in the literature. The best-fit line,

$$\text{Peak Flow (L/min)} = 2.346 \text{ Minute Volume (L/min)} + 20.828,$$

was very well determined, with $R^2 = 0.9867$. Data in the present study do not exactly fit Caretti's regression line. The R^2 value here is somewhat lower, but the slopes of the lines are similar. The lines are nearly parallel, with a difference in zero intercept. This is not too surprising due to the factors mentioned at the beginning of this discussion. Caretti analyzed historical data, some up to 50 years old.

As Caretti has noted, peak flow rates can be anticipated through the process of: 1) converting physical work rate into physiological work rate, 2) converting physiological work rate into oxygen demand, 3) determining corresponding minute ventilation, and 4) determining peak flow rates.

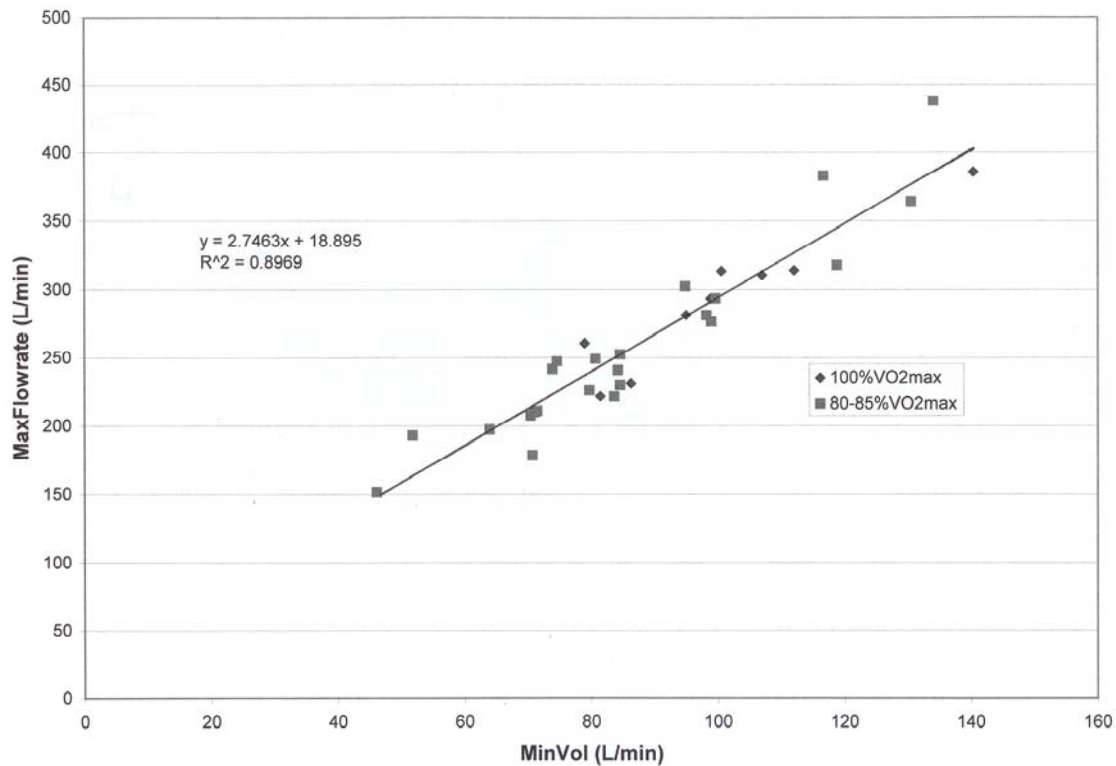


Figure 7. Maximum recorded flow rate for each subject related to average minute volume for subjects at 80-85% $\dot{V}O_2$ max (squares) and 100% $\dot{V}O_2$ max (diamonds). The presence of a strong predictive relationship between these two variables indicates a similarity of breathing waveshapes among the subjects. Peak flow rates persist for a very short time.

The close relationships between average minute volume and maximum inspiratory flow rate, and between average minute volume and average inspiratory flow rate can be used to advantage. Certainly for many purposes, further experimentation intended only to measure maximum and average inspiratory flow rates during strenuous exercise is unnecessary. Maximum and average flow rate can be calculated in the following manner:

1. Beginning with the work rate level, determine oxygen consumption. This can be determined by (Johnson, 1991):

$$\dot{V}O_2 = 0.00297 \dot{M} \quad (1)$$

where $\dot{V}O_2$ = rate of oxygen consumption, L/min

$\dot{M}$ = work rate, $N \cdot m/sec$ or Watts

2. Average respiratory minute volume can be calculated for average males, accounting for the hyperventilation above the ventilation threshold, by

(Johnson, 1993):

$$\dot{V}_{avg} = 22.34 \dot{V}O_2 + 1.53 \quad (2)$$

$$\dot{V}_{avg} \leq 1.55 \text{ L/min}$$

$$\dot{V}_{avg} = 22.34 \dot{V}O_2 - 5.03 + 11.51/(3.3 - \dot{V}O_2) \quad (3)$$

$$\dot{V}_{avg} > 1.55 \text{ L/min}$$

where $\dot{V}_{avg}$ = average minute volume, L/min

For highly-trained and larger individuals, these values would be increased.

For smaller or more sedentary individuals, $\dot{V}_{avg}$ would be lower.

3. Flow rates while breathing through respirator resistances have been found to be lower than unencumbered flow rates (Johnson, et al., 1999). Adjust flow rates for the effects of respirator inspiratory resistance:

$$\dot{V}_R = \dot{V}_{avg} - 4.12 \text{ R} \quad (4)$$

where $\dot{V}_R$ = average minute volume adjusted for inspiratory resistance, L/min

R = inspiratory resistance of respiratory apparatus, cm $H_2O \cdot \text{sec/L}$

4. Peak inspiratory flow rate can be calculated from the results we have obtained here:

$$\dot{V}_{peak} = 2.746 \dot{V}_{avg} + 18.895 \quad (5)$$

where $\dot{V}_{peak}$ = peak inspiratory flow rate, L/min

5. Flow rates may be adjusted for ambient conditions. Our results have been given for BTPS conditions. Inspired air is not at BTPS, but rather is at ambient conditions. The conversion is (Johnson, 1991):

$$\dot{V}_{amb} = \dot{V}_{BTPS} \left(\frac{273 + \theta}{310} \right) \left(\frac{p - 6.28}{p - p_{H_2O}} \right) \quad (6)$$

where $\dot{V}_{amb}$ = flow rates at ambient conditions, L/min

$\dot{V}_{BTPS}$ = flow rates at BTPS conditions, L/min

θ = temperature of ambient air, °C

p = total ambient pressure, kN/m² = 101.3 kN/m² normally

p_{H_2O} = partial pressure of water vapor in the ambient air, kN/m²,
which must be measured or estimated from a psychrometric chart.

The fact that there is a definite relationship between peak flow and average flow indicates a similarity among flow waveshapes from all subjects. If this were not so, the data would be much more scattered and the regression line would have a much lower regression coefficient. For example, peak-to-average values for square waves are 1.0, for half sine waves are $\pi/2$, for triangular waves are 2, and for trapezoidal waves are between 1 and 2, depending on the ratios of the maximum and minimum heights. If the peak-to-average ratio were random, then no statement could be made about the waveshape. However, there was a definite peak-to-average ratio of 2.75 found for this data, and the flow waveshapes shown in Figures 1 and 4 are typically seen for subjects breathing hard. Thus, it is reasonable to conclude that breathing flow waveshapes during heavy exertion are universally determined by respiratory mechanical properties that were nearly the same for all our subjects.

One must be somewhat careful because minute volume is conventionally measured in terms of BTPS conditions (although often this is not designated), whereas the rate of oxygen use is measured at

STPD conditions (Johnson, 1991). Although the above calculations are valid for the average young male adult, the results can be adjusted for other types of respirator wearers.

There are a number of uncertainties regarding respiratory flow rates that make difficult the interpretation of published experimental results. First among these is what is meant by minute volume, and, relatedly, by average flow rate. Minute volume was originally defined as the volume of air inspired per minute, and was equal to the inspired tidal volume multiplied by the respiration rate (Ganong, 1963). However, it is often more convenient to measure exhaled flows, so many minute volume measurements are made during exhalation. Exhalation volumes can often exceed inhalation volumes by 20% or more, depending on temperature and humidity conditions of measurement (Johnson, 1991).

Minute volume has often been used synonymously with average flow rate, incurring even more uncertainty. The period of time for average flow rate is not specified, and is usually longer than the one minute duration for minute volume. Also, because flow rate is bidirectional, the average flow rate for a whole breath (volume inhaled or exhaled divided by the entire breath interval) is different from the average flow rate for either inhalation or exhalation. Average flow rate is sometimes taken to be the accumulated exhaled volume over a long period of time (say, five or fifteen minutes). Again, it is common to call this minute volume.

Reports in the literature are often not clear on the basis for these flow rates. Are they given in STPD, BTPS, or ambient conditions? Although this is sometimes made clear, this is not always the case.

The result of all this is that precise measurements of respiratory flow rates may be made, but, unless it is exactly clear what is being reported, there is a great deal of uncertainty regarding the use of those measurements. Add to that the natural variation within the population and different responses obtained during different activities (breathing during heavy lifting, for instance, is different from breathing during running), and one can only say that there will be design trade-offs for respiratory protective devices. If a device were to protect 100% of the population 100% of the time, the device might be either too expensive, too heavy, or have a useful life too short to be practical. On the other hand, a device used by a small percentage of the population 100% of the time might be necessary for specific uses where uncertain, but potentially immediately dangerous to life or health (IDLH) contamination exists. Different respirators for different applications may be required to meet different respiratory demands.

This study was performed in the laboratory under controlled conditions. Subjects were young, healthy, and walked on a treadmill in a benign environment that was not likely to cause heat stress, anxiety, or sudden changes. So, how applicable are these results to workers who may be older, performing different tasks in harsher environments, and who may have to react to rapid changes in conditions? Despite the realistic nature of the tasks performed in the Kaufman and Hastings study, their study was still a simulation, as are all of these studies, and it is difficult to know exactly what physiological responses would be obtained from people in real situations. It is likely, however, that breathing flow rate data obtained from $\dot{V}O_2$ max tests would not be exceeded under any circumstances.

Now that we have some breathing flow rate data, what can be done with it? Peak flow rates do not represent a very large portion of the flow rates incurred during breathing. Because these flow rates represent only a small fraction of time for a small fraction of the population, overall protection of the wearer population is not necessarily measurably better if the peak flows are accommodated or not by the respirator. A lot depends on the type of respirator used, how it is used, and how it is worn. It has been shown that respirator resistance leads to hypoventilation (Johnson et al., 1999), so peak flows are reduced accordingly. If a small amount of contaminated air enters the facepiece through face seal leakage or through momentary breakthrough of the filter, the wearer's health is not necessarily going to be compromised. Only in the most dangerous situations will the failure to supply necessary peak respiratory flow be critical. Sometimes these situations can be controlled and sometimes they can't. If they can't then the choice of a respirator and filter must be made very carefully.

CONCLUSIONS

Peak flow rates vary greatly among subjects. Peak flow rates at 80-85% $\dot{V}O_2$ max can reach 359 L/min. Peak flow rates for 100% $\dot{V}O_2$ max exceed those measured for 80-85% $\dot{V}O_2$ max. Measured flow rates for the pressure-demand PAPR are higher than breathing flow rates. Estimated peak flow rates can be calculated for various strenuous work conditions.

This work was funded in part by the National Institute for Occupational Safety and Health (NIOSH Contract 200-2002-00531). The findings and conclusions in this report are those of the authors and do not necessarily represent the views of NIOSH.

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