Peak Inhalation Air Flow & Minute Volume during a Controlled Test Performed on an Ergometer

Göran Berndtsson (Author)
The S.E.A. Group
Los Angeles

Flisa Berndtsson, Sara Jessup, Tara McNamara (Assistance and Data Collection)
The S.E.A. Group
Sydney, Australia

Introduction

This study was performed by The SEA Group at their Human Subject Test Laboratories in Sydney, Australia. Five negative pressure full face mask respirators and one positive pressure demand powered air purifying respirator (PPDPAPR) were used in this test.

The results of this test emphasize that we at present do not test respiratory protective devices (RPD) adequacy to ensure that the user can use the RPD without undue physiological burden (breathing resistance), nor can we with confidence ascertain that the RPD will actually offer the protection the user expects or should be entitled to get from a product which is certified and/or deemed to comply with NIOSH, CE or Australia/NZ standards.

[illegible]

d a final statement of NIOSH policy or of any agency or individual who
for use in advancing knowledge needed to protect workers. Comments
ted to the NIOSH Docket Office

1. [illegible] earlier findings by the author as well as [illegible]*nical Protection,* Professor I. Holmér, [illegible] Åstrand, *Textbook of Work Physiology.*
2. The work which best represent a first responder's typical work (150 Watt external work) generates high PIAF rates, all in excess of the typical test flows, raising the question, how well will the first responder be protected if we don't test at a typical flow rate for this type of work?
3. At 150 Watts external work, a full 90% of the inhalation sequence is made up of air that flows faster than 115 lit/min without speech. A whole 42% flows faster than 200 lit/min.
4. In order to maintain positive pressure for 95% of all first responders, an air flow of 367 lit/min is required (this is based on flows measured in negative pressure full face masks).

Based on this data and data collected and presented by Dr. J. Kaufman,(*Respiratory Airflow in Working Individuals Wearing Chemical Protection),* and Professor I. Holmér, (*Respiratory flow patterns during physical work with respirators)* as well as what's published in all modern text books in Physiology in particular Sport Physiology I propose the following recommendations for the New Standards for RPD for use by First Responders and other who need protection in CBRN situations.

1. To maintain the level of protection required when exposed to hazards typically classified as CBRN compound's, we need a performance level which will assure that a so called Positive Pressure respirator really maintain Positive Pressure. Based on the Data collected and presented recently (*"Peak Inhalation Air Flow during an Agility Test Performed by the US Marine Corps"}* , and if we want to protect the 95% tale, then we need RPD's to maintain Positive Pressure at 427 lit/min.
2. The RPD shall have an alarm to warn the user when Positive Pressure can no longer be maintained during a substantial portion of the inhalation cycle (filter clogged, battery voltage low or work rate to high).

Background

The inhaled air passes through a filter or filters, a fan unit and/or a face mask, and then to the lungs of the wearer. Any respirator being of the positive pressure demand or negative pressure type needs to be carefully fitted to minimize the risk of face seal leakage, so only filtered air is distributed to the lungs, where the oxygen will be extracted into the bloodstream.

One identified limitation is the capability to maintain a sufficient amount of supplied air to the user by equipment such as PAPRs and the so-called positive pressure respirators which are tested and approved to existing standards.

This study was designed to simulate different work intensities which are common when workers are required to wear RPD when performing their assigned tasks. We decided to use an ergometer (test bicycle) to simulate the different workloads; most people would be comfortable riding a bicycle.

*NOTE: To avoid misunderstandings, the term **liters/minute is used** when referring to PIAF (Peak Inhalation Air Flow) and **minute liters** when referring to volume of air.*

Material and methods

The equipment used comprised five negative pressure full face masks and a [PPD-]FPBR ([Positive Pressure Demand]-Fan-supplied Positive pressure Breath Responsive Respirator) model SE400AT (listed below); the aim was to get a range of both inhalation and exhalation resistance.

A silicone full face mask with two exhalation valves and only the filter used for the flow measurement was used for low resistance with a pressure drop of -0.4 millibar at 85 liters/minute for inhalation and a pressure drop of +0.14 millibar at 85 liters/minute exhalation.

The second RPE was an SEA full face mask with a NIOSH-approved (National Institute for Occupational Safety and Health) DP (Domestic Preparedness) filter plus the flow meter with a pressure drop of -2.8 millibar at 85 liters/minute for inhalation and a pressure drop of +0.9 millibar at 85 liters/minute exhalation.

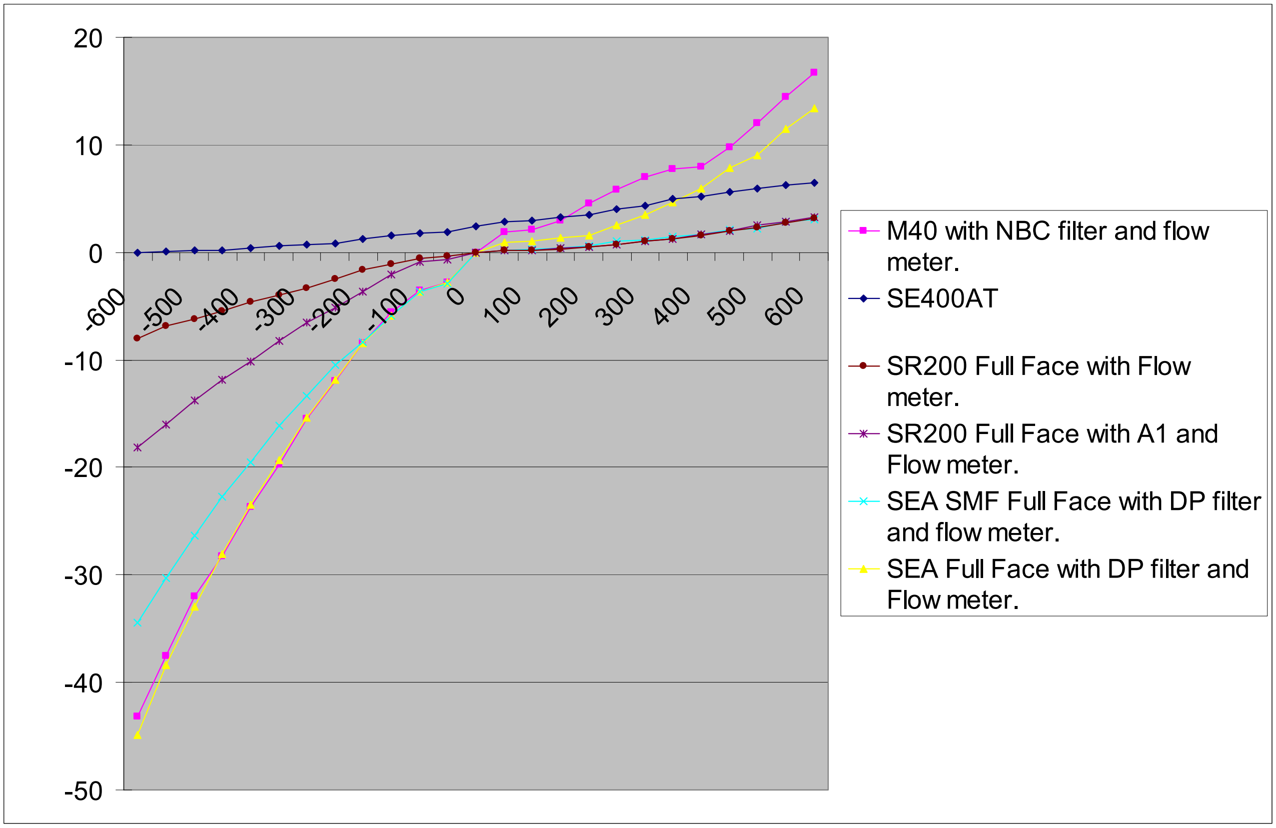
The third RPE was an M40 with a US NBC military filter and the flow meter with a pressure drop of -2.81 millibar at 85 liters/minute for inhalation and a pressure drop of +1.87 millibar at 85 liter/minute exhalation.

The fourth RPE was an SEA SE400 respirator. We used only the flow meter, as the filter as the performance of equipment is independent of the pressure drop over the filter, with a pressure drop of +1.875 at 85 liters/minute for inhalation and a pressure drop of +2.45 millibar at 85 liter/minute min exhalation.

The fifth RPE was a silicone full face mask with two exhalation valves, the filter used for the flow measurement was an A1P3 (organic vapor and particulate P100) with a resistance pressure drop of -0.65 millibar at 85 liters/minute for inhalation and a pressure drop of +0.14 millibar at 85 liters/minute exhalation.

The sixth RPE was a SEA SMF of Halo Butyl material with side-mounted filter, one exhalation valve, with a DP filter (Domestic Preparedness) with a resistance pressure drop of -2.9 millibar at 85 liters/minute for inhalation and a pressure drop of +0.23 millibar at 85 liters/minute exhalation.

The graph below shows the pressure drop for inhalation and exhalation flows up to 600 lit/min.



Test equipment used

Using a Monark 839E Ergomedic Test Bike connected to a computer, a test protocol was developed using the software supplied with the test bike.

We started at a work rate of 50 W (Watts), increasing the rate every five minutes by 25 W and stopping after 40 min or when the test subject reached 85% of the theoretical maximum heart rate (227 minus the subject's age for women or 220 minus the subject's age for men multiplied by 0.85).

The test was also discontinued if the %SpO_2 (percent oxygen saturation) went below 92% or if the subject felt distress.

The heart rate was measured using POLAR S610 heart rate monitors, downloading to POLAR software.

We measured %SpO_2 using an Onyx 9500 Finger Pulse Oxymeter.

The volume of air breathed through the respirator (VO) was measured, as well as PIAF (Peak Inhalation Air Flow) using a flow/volume meter based on pressure-drop change over a known resistance, These meters are very fast, recording at 50Hz, which gives an outstanding resolution and makes it possible to record the very fast changes that occur when inhaling in conjunction with speech (see appendix 2).

When measuring PIAF, a flow meter based on pressure drop is a good choice, as it is as fast as required (necessary to measure liters per millisecond).

The pressure drop over the resistance is not linear. The discrepancy between the true flow and the measured flow is described in the table below (Table 1).

For this test, we chose a simple solution: we calibrated the flow meter at 200 liters, as we expected this to be in the area where we would see most information.

Table 1

True flow (liters/minute)	Measured flow (liters/minute)	% error
400	472	+18
300	342	+14
200	201	±0
175	162	–7.5

Conditions in the test room: temperature 23 ±3 degrees Celsius and humidity 47% ±5%.

All data has been recalculated back to STPD (Standard Temperature Pressure Dry) for ease of comparison with other data.

The heart rate was measured with Polar Electro heart rate meter (S610).

Subjects

Ten test subjects (8 male and 2 female) participated in the study. Anthropometric details are given in table 2.

Table 2

	Average All Subjects	Standard deviation	Min	Max
Age	34	13.6	17	54
Weight kg	77	12.7	61	96
Height cm	179	7.7	169	193

Test Procedures

The test was carried out by The SEA Group, at their Human Subject Test Laboratories in Sydney, Australia.

The subjects were dressed in gym clothing (shorts, t-shirts and sneakers).

An introduction to the reason for the test and an opportunity to get familiar with the different test masks were given before the test.

The protocol was as follows:

The test was divided in to eight five-minute sections, each with different external workload, starting at 50 Watts external workload, increasing by 25 Watts every 5 minutes. This resulted in the highest section being 225 Watts external workload.

Within each section, during the first tree minutes, the test subject could pedal the bike with no interference. This allowed the subject's heart rate and breathing pattern to equalize.

During the fourth minute, the test subject was required to read aloud as when talking normal. We used the text applied in testing RPEs, i.e. **The Raindrop sentence**; "*When the sunlight strikes raindrops in the air […]".* This reading was repeated for one minute.

During the fifth minute, the subject pedaled before the program automatically increased the resistance by 25 W.
The sequence was then repeated, over and over again, until we reached either forty minutes or 85% of max heart rate.

(See test program appendix 1.)

Results (this report includes the data for the first five work load sections 50 Watts to 150 Watts)

As has been written by many authors[8.9.10] of research before me, the result clearly shows that a human can breathe very high volumes with very high PIAF's.

The spreads of both volume and PIAF were large. The average minute volume was 22.20 minute liters (when talking in the first work section) — 61.57 minute liters, and the average PIAF was 99.49 lit/min to 268.02 lit/min (with maximum PIAF reaching 533.73 lit/min).

The heart rate was linear to the workload, independent of the breathing resistance. This is what we expected. [1,9]

The %SpO_2 — per cent oxygen saturation in the blood — was between 99%-92%.

The reduction occurred in particular when a RPE with high pressure drop was used at a higher work load and while speaking.

These factors interfere with the breathing frequencies to such a degree that %SpO_2 decreased.

This is what Silverman concluded in his research.[8,9,10] The implication of this should be investigated more (see attached appendix 3 *Oxygen Consumption and Delivery Summary* by Dr B. M. Drew).

No test subject could continue to a workload of 225 W and still remain below 85% of theoretical heart rate.

The results for work level 1 (50 Watt at the test bike) this is a conclusion of 63 test results:

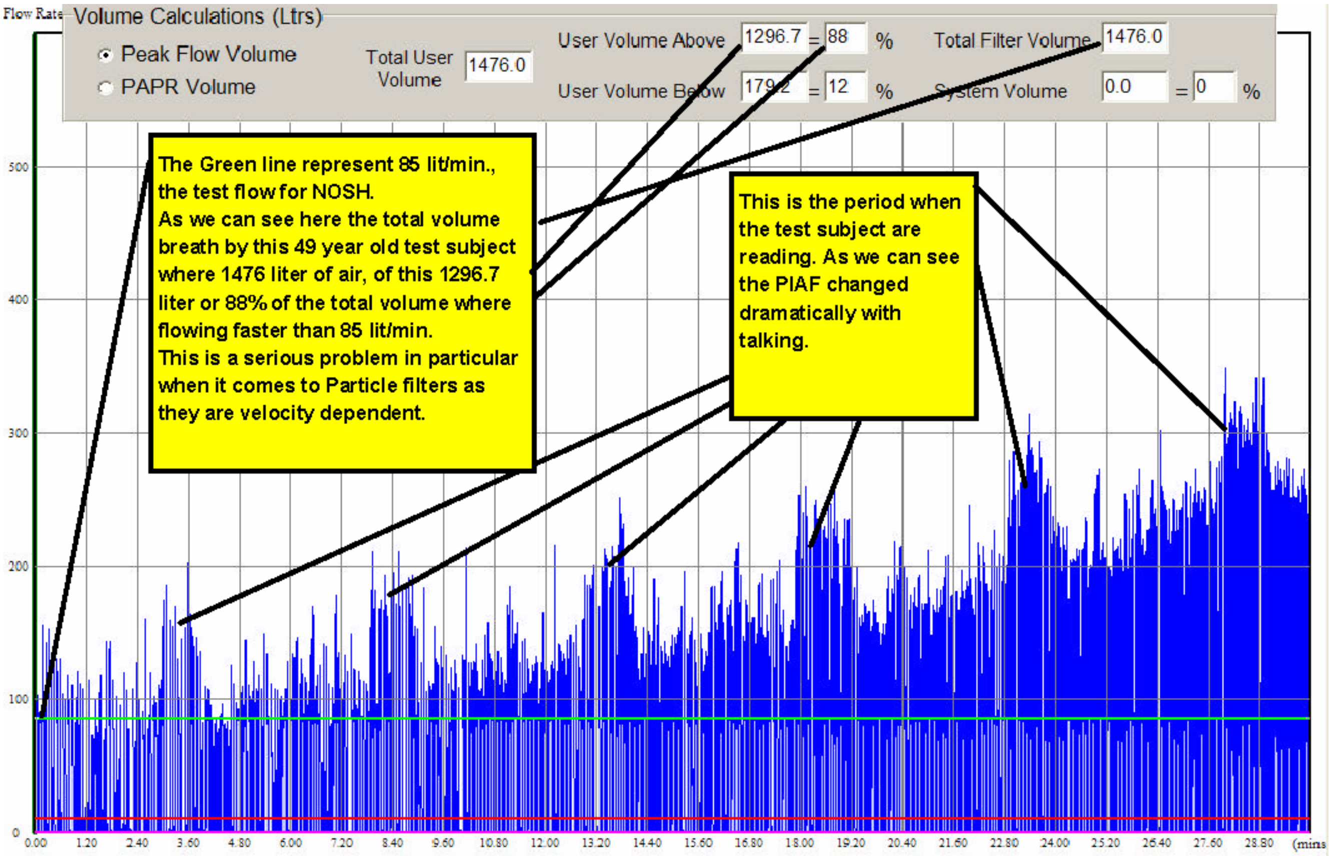
Average minute volume at the third minute 26.39 minute liter with an average PIAF of 101.4 lit/min.

The fourth minute including speech the volume dropped to 22.20 minute liters; this is a drop of 16% for the volume. The PIAF increased to an average of 177.86 lit/min, an increase of 75% over the PIAF before speech.

In the fifth minute, the recovery minute before workload increased by 25 Watt, the volume rose to 30.10 minute liter — an increase of 14% compared with the minute just before speech.

This pattern was consistent all through the test. As the workload increases and the test subjects get closer to their theoretical maximum, the difference between average PIAF with and without speech becomes smaller.

Below is a sample of a typical graph of 30 minutes test with one of the test subjects.



Data

The importance of PIAF (Peak Inhalation Air Flow)

If the PIAF is higher than the supply capability of the PAPR, the performance protection of the PAPR is not higher than its face mask as a negative pressure respirator — in this case a full face mask — and what influences the performance is the capability to seal against the face at all different pressure drops.

The performance of the filters also plays a role at this high PIAF. As mentioned earlier, the particulate part of the filter is influenced by the velocity of the air moving through it.

It is commonly accepted that a gas filter's capacity against organic compounds is not significantly influenced by higher air flow (pulsating flow has been verified by NIOSH). The performance against acid and ammonia has yet to be verified at higher flow (pulsating flow).

As shown in Table 3, the average PIAF for (Low External Work Load 50 Watt) is 131.25 lit/min with a Maximum of 402.13 lit/min.

Table 3

	Number of tests	**Volume of air (minute liters)**	**Average PIAF**	**Max**	**Volume of air minute liter flowing faster than test speed 85 liter.**
Minute before speech (50 Watt external work load)	63	26.39	99.49	252.68	11.79 liter (44.7%)
Speech	63	22.20	174.05	402.13	20.14 liter (90.7%)
Consolidated the minute before and speech.	63	24.295	131.25	402.13	

The frequency distribution of the consolidated data for 50 watt external work load is shown in Table 4, and Graph 1.

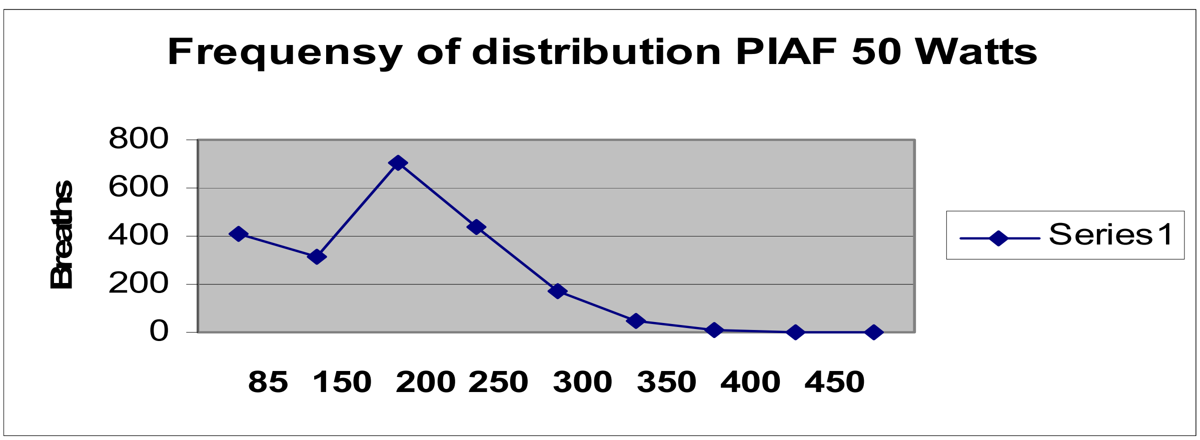
Table 4

PIAF (lit/min)	Number of breaths	%
Less than 85	412	19.60
85-100	311	14.80
100-150	709	33.73
150-200	435	20.69
200-250	170	8.09
250-300	52	2.47
300-350	11	0.52
350-400	1	0.05
400-450	1	0.05
Total	2102	100.00

Table 5

	Lit/min peak flow
95th Percentile	232
87th Percentile	195
80th Percentile	176
70th Percentile	153
60th Percentile	135
50th Percentile	119
40th Percentile	106
30th Percentile	95
20th Percentile	85
10th Percentile	74

Graph 1



This shows a typical distribution curve. 34% of the peak flows ranges from 100 to 150 lit/min.
The 95th percentile is 232.09 lit/min at an external work load of 50 Watts, which means that in order to maintain positive pressure all the time for 95% of the population, the PAPR must have an airflow of 232.09 lit/min (see table 5).

What does 50 Watts of external work represent?

Sitting at ease; light manual work (writing, typing, drawing, sewing, book-keeping); **hand and arm work** (small bench tools, inspection, assembly or sorting of light material); **arm and leg work** (driving vehicle in normal conditions, operating foot switch or pedal).

Standing: drill (small parts); milling machine (small parts); coil winding; small armature winding; machining with low power tools;

Casual walking; (speed up to 3.5 km/h or 2.2 mph).

This is not hard work and possibly not representative for the first responders, so lets have a lock on work load more representative for this user group.

A more appropriate work level would possibly be what we in the new ISO working group refer to as Very High Work Load (ISO 8996:1990 Annex A Very High Metabolic rate of 520Watt)

This translates to approximately 150 Watt external work. We can describe this as: **Very intense activity at fast to maximum pace**; working with an axe; intense shovelling or digging; climbing stairs, ramp or ladder; walking quickly with small steps, running, or **walking at a speed** greater than 7 km/h or 4.4 mph.

This work is more applicable to a first responder, for instance, who needs a respirator for CBRN protection.

As shown in Table 6, the average PIAF for Very High External Work Load (150 Watt) is 268.02 lit/min with a Max of 533.73 lit/min.

Table 6

	Numbers of tests	**Volume of air Minute liter**	**Average PIAF**	**MAX**	**Volume of air minute liter flowing faster than test speed 85 liter.**	
Minute before speech 150Watt external work load	43	57.34	176.52	320.05	52.94 liter	92.33 %
Speech	43	49.58	268.02	533.73	48.02 liter	96.88 %
Consolidated the minute before and speech.	43	53.46	217.96	533.73		

The frequency distribution of the consolidated data for 150 watt external work load is shown in Table 7, and Graph 2.

Table 8 shows, for example, that the regular flow for standard PAPR's does not even provide sufficient airflow to the 10^{th} percentile.

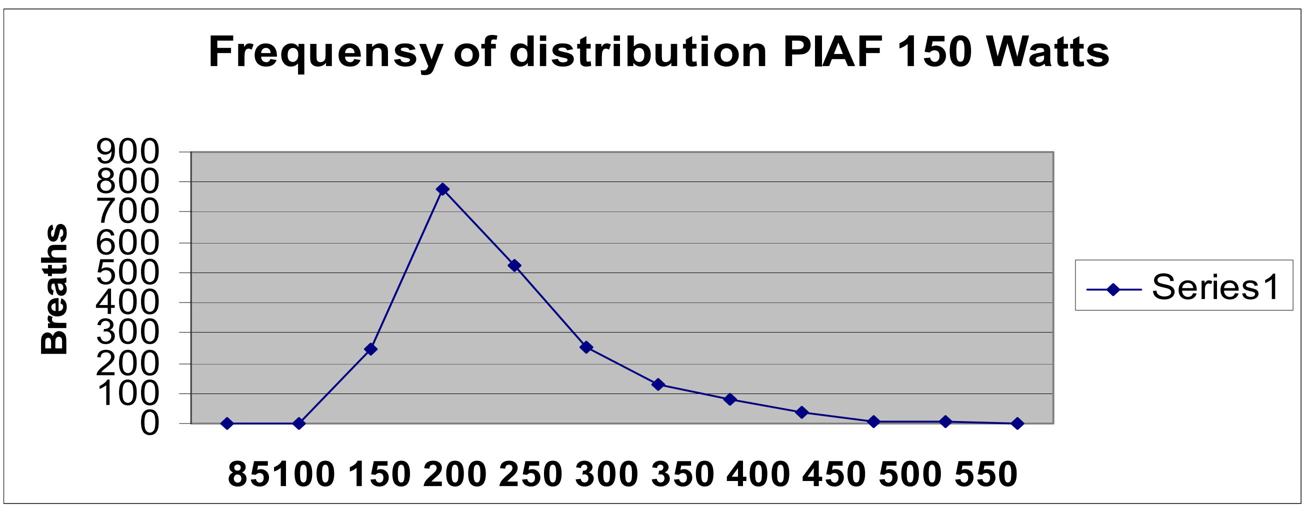
Table 7

PIAF (lit/min)	Number of breaths	%
Less than 85	0	0
85-100	1	0.05
100-150	247	11.99
150-200	776	37.67
200-250	524	25.44
250-300	252	12.23
300-350	127	6.17
350-400	82	3.98
400-450	38	1.84
450-500	5	0.24
500-550	8	0.39
Total	2060	100.00

Table 8

	Lit/min peak flow
95th Percentile	367
87th Percentile	296
80th Percentile	265
70th Percentile	237
60th Percentile	217
50th Percentile	201
40th Percentile	188
30th Percentile	175
20th Percentile	161
10th Percentile	147

Graph 2



Conclusions:

- Inspiratory air flow rates are high for all exercises. This concurs with earlier findings by the author as well as by Dr. J. Kaufman, *Respiratory Airflow in Working Individuals Wearing Chemical Protection,* Mr. I. Holmér, *Respiratory flow patterns during physical work with respirators*, and Dr. P-O. Åstrand, *Textbook of Work Physiology.*
- The work which best represent a first responder's typical work (150 Watt external work) generates high PIAF rates, all in excess of the typical test flows, raising the question, how well will the first responder be protected if we don't test at a typical flow rate for this type of work?
- At 150 Watts external work, a full 90% of the inhalation sequence is made up of air that flows faster than 115 lit/min without speech. A whole 42% flows faster than 200 lit/min.
- In order to maintain positive pressure for 95% of all first responders, an air flow of 367 lit/min is required.

Future work:

The test outlined here forms part of a wider spectrum of respirator research, and further work is in progress.

This should serve to give us a broader picture of the relationship between work rate, breathing resistance and PIAF in people of all ages and fitness levels.

References:

1. Åstrand, P.O., Rodahl, K., 1986 (1970), Textbook of Work Physiology: Physiological Bases of Exercise, 3rd ed., McGraw-Hill Book Co. International Series, New York
2. Dahlbäck, G. O., Navak, L., 1983, *Do Pressure-Demand Breathing Systems Safeguard against Inward Leakage?*, Am. Ind. Hyg. J., vol. 44(5), pp 336–340
3. Jackson, B. A., Peterson, D. J., Bartis, J. T., LaTourette, T., Brahmakulam, I., Houser, A., Sollinger, J., 2001, Protecting Emergency Responders: Lessons Leaned from Terrorist Attacks, [Conference Proceedings — NIOSH/RAND Personal Protective Technology Conference Dec 9 11, 2001], RAND Science and Technology Policy Institute, New York City
4. Johnson, A. T., Scott, W. H., Lausted, C. G., Benjamin, M. B., Cove, K. M., Sahota, M. S., Johnson, M. M., 1999, Effect of Respirator Inspiratory Resistance Level on Constant load Treadmill Work Performance
5. Myhre, L. G., Tucker, D. M., Bauer, D. H., Fischer, J. R. Jr., (undated), *Relationship between Selected Measures of Physical Fitness and Performance of a Simulated Fire Fighting Emergency Task*, Crew Systems Directorate, AL/CFT Systems Research Branch, Brooks AFB, Texas
6. ———, (undated), *Physiological Criteria for the Valid Selection of Workers Who Must Perform Physical Tasks while Wearing Protective Equipment*, U.S. Air Force Research Laboratory, Brooks Air Force Base, Texas
7. Raven, P. B., Dodson, A. T., Davis, T. O., 1979, *The Physiological Consequences of Wearing Industrial Respirators: a Review*, Am. Ind. Hyg. J., vol. 40, pp 517–534
8. Silverman, L., Lee, R. C., Lee, G., Drinker, K. R., Carpenter, T. M., 1943, Fundamental Factors in the Design of Protective Respiratory Equipment. Inspiratory air flow measurements on human subjects with and without resistance, Departments of Physiology and of Industrial Hygiene, Harvard School of Public Health, and the Nutrition Laboratory of the Carnegie Institute of Washington
9. ———, Billings, C. E., 1961, Pattern of Airflow in the Respiratory Tract, Harvard School of Public Health, Pergamon Press
10. ———, Lee, G., Plotkin, T., Sawyers, L. A., Yancey, A. R., 1951, Air Flow Measurements on human subjects with and without respiratory resistance at several work rates, Ind. Hyg. And Occ. Medicine, vol. 3
11. Wallaart, J., Winder, C., (yet to be published), *The Determination of Total Inward Leakage to Validate the likely Performance of Respirators in the Workplace and the Importance of "Calibrating" Test Subjects to Determine the Total Inward Leakage of Respirators*
12. ———, (yet to be published), *The determination of Minute Air Flows and heart Rates for a Typical Industrial Work Group at Various Levels of Work*
13. ———, (yet to be published), *The Determination of Peak Inspiratory Air Flows (PIAF) at Various Levels of Work and the Increased Air Flows that Result when Communicating in the Workplace*
14. Berndtsson, G., Ekman, L., Jessup, S., Berndtsson, F., 2002, *Ventilation Volume and PIAF when Wearing Negative and Positive Pressure Respirators*, presented at International Society for Respiratory Protection Conference, Edinburgh, Scotland, 02 Oct
15. Holmér, I., Kuklane, K., 2002, *Respiratory Flow Patterns during Physical Work with Respirators*, Department of Ergonomics, National Institute for Working Life, Solna, Sweden
16. Kaufman, J., 2000, *Initial Findings: Respiratory Airflow in Working Individuals Wearing Chemical Protection*, presented at NIOSH/NIST/SBCCOM Public Meeting, Canonsburg, Pennsylvania, USA, 16 Oct
17. Wallaart, J., Winder, C., *The Determination of Peak Inspiratory Air Flows (PIAF) at Various Levels of Work and the Increased Air Flows that Result when Communicating in the Workplace*

18. Wallaart, J., *The Determination of Minute Air Flows and Heart Rates for a Typical Industrial Work Group at Various Levels of Work*

Appendix 1

Start

Time	Workload	Activity	Metabolic rate
1 Min 2 Min 3 Min 4 Min 5 Min	Pedalling the test bike at 50 Watts external workload	No talk Reading "the rainbow sentence" aloud Catching the breath after talking	Low metabolic rate (Class 1 Annex A ISO 8996:1990) This is equal to a man walking at 3.5 km/h (2.2 miles/h).
6 Min 7 Min 8 Min 9 Min 10 Min	Pedalling the test bike at 75 Watts external workload	No talk Reading "the rainbow sentence" aloud. Catching the breath after talking.	
11 Min 12 Min 13 Min 14 Min 15 Min	Pedalling the test bike at 100 Watts external workload	No talk Reading "the rainbow sentence" aloud. Catching the breath after talking.	Moderate metabolic rate (Class 2 Annex A ISO 8996:1990) This is equal to a man walking at 3.5 km/h to 5.5 km/h (2.2 miles/h to 3.4 miles/h).
16 Min 17 Min 18 Min 19 Min 20 Min	Pedalling the test bike at 125 Watts external workload	No talk Reading "the rainbow sentence" aloud. Catching the breath after talking.	High metabolic rate (Class 3 Annex A ISO 8996:1990) This is equal to a man walking at 5 km/h to 7 km/h (3.4 miles/h to 4.4 miles/h).
21 Min 22 Min 23 Min 24 Min 25 Min	Pedalling the test bike at 150 Watts external workload	No talk Reading "the rainbow sentence" aloud. Catching the breath after talking.	Very high metabolic rate (Class 4 Annex A ISO 8996:1990) This is equal to a man walking at greater than 7 km/h (4.4 miles/h).

SEA PORTABLE BREATHING RECORDING EQUIPMENT

SEA has various types of computer-based equipment to measure and record breathing curves.

At the 2000 ISRP conference in Sydney, a simple portable device was created to show human breathing accurately, displaying a curve tracking the breathing volume in real-time, using any respirator.

The device comprised a simple pressure transducer and a particle filter, and was built on the following principle: if the resistance and the pressure drop across the resistance are known, the flow rate through the resistance can be calculated.

The device was built with the aim to minimize air turbulence etc. to give as accurate a reading as possible.

With modern computers there is no need to calculate the values. Instead, simple programming can convert the raw data to the desired format using calibration points.

The device is meant to clearly show all parts of the breathing curve such as the different faces of inhalation, rest, and exhalation and not just record the peak value. To achieve this, the device records the data at a rate of fifty (50) samples per second.

The device is then calibrated or, more precisely, the software is given a raw data reading, and given the parameter that “this is the flow of x”.

The respirator is fitted to a “head” connected to an air pump and a calibrated mechanical flow meter to record the airflow for continuing airflow at the calibration points.

For a final test the respirator is fitted to a calibrated breathing machine and the graphs produced are compared to the graphs from the breathing machine.

The end result is a detailed breathing curve, not to be confused with the “industry” breathing curve.

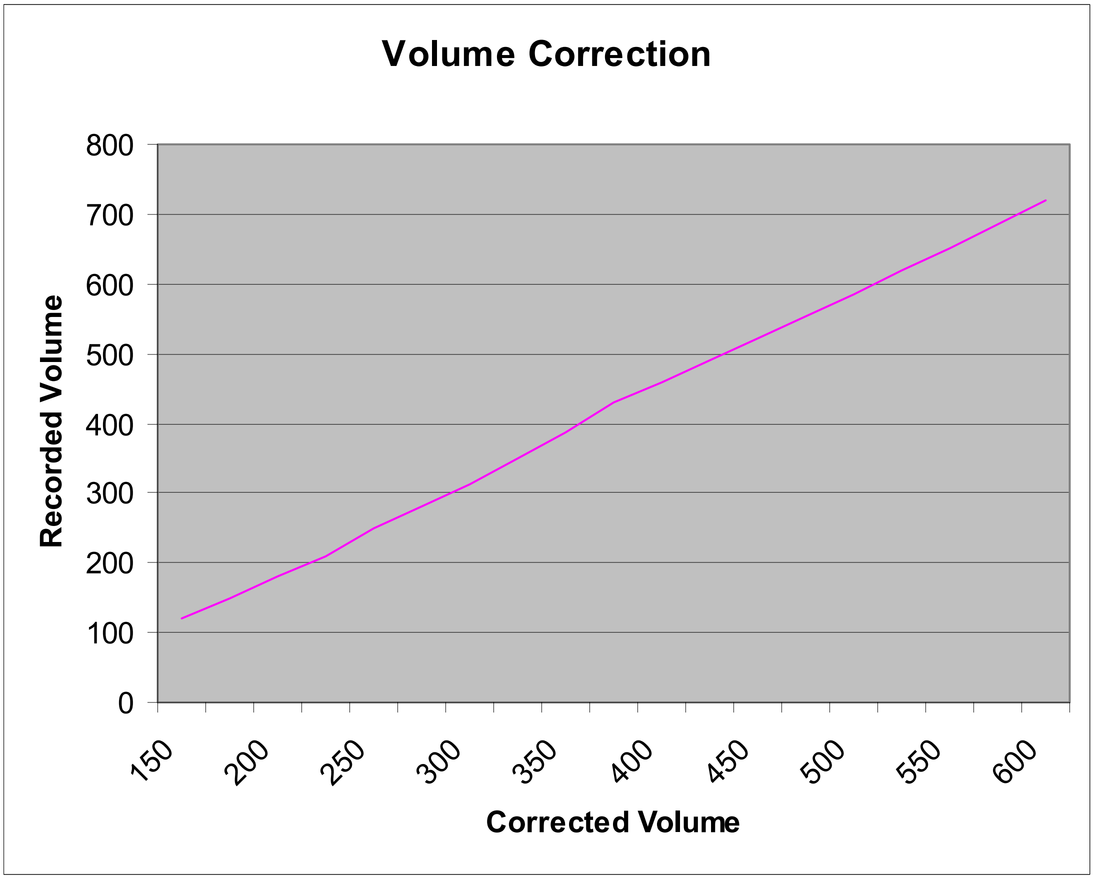
The accuracy is gained from two main factors:

- The **timing** of the events is set to fifty times per second. This frequency produces a nice curve and a reasonable collection of data. At first, samples where collected at a rate of 300 per second, but no degradation was seen for the lower value and a significant saving was made in terms of data storage.
- The **actual flow value** is shown. The original request was for a “show and tell” at the Sydney conference; hence an accuracy of ±15% was seen as sufficient in the range of 100 to 400 liters.

The equipment has since been used much more and has been given a higher profile than was originally expected.

It could have been relatively simple to improve on the accuracy, but in order to be able to mix historic data with new data and to use statistics from many different occasions, it was decided to keep the settings fixed.

As the data recorded is only changed in a linear fashion and as the calibration error is known, a simple correction curve can be used if so desired.



It should be noted that the original display was limited at 550 liters. However, all subsequent use has been of the raw data in other SEA programs.

The data recorded is highly accurate; the turbulence in the mechanical air flow meter used for calibration is the weak point, causing fluctuations in the gauge.

In summary, the corrected curve is as accurate as the calibrated mechanical flow meter used for calibration, the difference being that only steady flows can be measured, whereas the SEA device can measure dynamically changing flows.

Finally, all SEA test equipment (including mechanical and computer-driven equipment) is highly accurate and carries calibration labels and is subjected to quality control. This specific device is not, however, but is still as accurate as the equipment used to calibrate, and the calibration is regularly checked.

Please note:

- The recorded/corrected volume referred to in the graph is actually the flow rate measured in liters per minute and not volume.
- The recording is of flow and time only. Other programs, such as the SEA EDL, are used to calculate volume, number of breaths, etc.
- Mechanical flow meter SEA NO: L Calibration Date 1/5/03
- Breathing machine SEA NO: I8 Calibration Date 3/1/04

Appendix 3

Oxygen Consumption and Delivery

Summary

Dr Billy Markus Drew MBBS
3/16 Whiting Ave
Terrigal, NSW 2260
AUSTRALIA

Consumption

- Resting oxygen consumption is 250mls/min
- This increases up to 4000mls/min in heavy exercise to enable aerobic metabolism of body's stored fuels.
- Aerobic metabolism (using O_2) is a far more efficient way to use stored fuel (simplistically about 18 times in the initial conversion phase) than burning fuel anaerobically (without O_2)

Delivery

- O_2 delivery to the tissues is dependent on the oxygen flux equation
  - Delivery O_2 (ml O_2/min) = Cardiac Output (100mls/min) x [haemoglobin concentration (g/100ml) x saturation of O_2 (%) x 1.34 (ml/g) + partial pressure of O_2 (mmHg) x 0.003 (ml/100ml/mmHg)]
  - Each gram fully saturated haemoglobin contains 1.34mls of O_2 (4 molecules)
  - Normal haemoglobin=15g/100ml $\therefore$ 1.34ml/g x 15g/100ml = 20.1ml O_2/100ml blood (if 100% saturated)
  - Dissolved O_2 is linear = 0.003 ml/100ml/mmHg PO_2 (negligible in terms of content of O_2 compared to haemoglobin)
  - Not all blood goes through the lungs (physiological shunt) therefore arterial blood is usually 97% saturated (strangely enough is equal to PO_2 97mmHg)
    - $\therefore$ 20.1x97/100 +0.003x97 = 19.8 mls O_2 / 100ml blood
    - At rest if cardiac output = 5L/min → O_2 delivery = 990mls O_2/min (lungs to tissues)
    - This is about four times resting O_2 consumption
  - THUS, equation can be simplified to
    - $DO_2 = CO \times Hb \times SO_2 \times 1.34$
  - What does all this mean?

The delivery of oxygen to the tissues is dependent on cardiac output which is normally 5 l/min but can increase to 25 l/min in severe exercise (i.e. 5 times)

- It is also dependent on the haemoglobin concentration. This can be considered constant in everyday people but women usually have slightly less than men.
- Finally, it is dependent on the saturation. This is dependent on the minute ventilation (l/min ventilated through lungs) and the inspired oxygen concentration (air has 21% oxygen). To a lesser degree, it is also dependent on cardiac output. Usually each blood cell takes 0.75 seconds to pass through the lung capillary but when the cardiac output is very high, such as during severe exercise, the red blood cell has less time in the lung capillary and therefore has less time for the oxygen to attach to the haemoglobin molecule.

Oxygen Saturations

- Diffusion of oxygen depends on the partial pressure gradient of O_2 between the blood and tissues
  - The relationship between oxygen content and partial pressure is via the oxy-haemoglobin dissociation curve

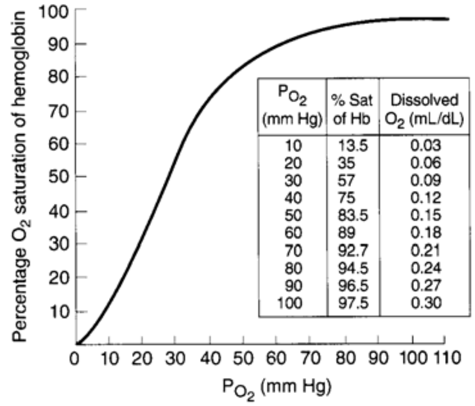


Figure 35–2. Oxygen-hemoglobin dissociation curve. pH 7.40, temperature 38 °C.

- This is a sigmoid curve – a normal arterial saturation is about 97%
- Venous blood saturations are about 75%
- Thus, in the lungs a big change in partial pressure of oxygen does not affect the saturation that much but at a tissue level a small change in PO_2 is associated with a more unloading of O_2 for use by muscles etc
- In strenuous exercise it should be noted that the above curve can shift to the right to increase oxygen extraction up to 3 times

- What does a drop in O_2 saturations mean?
  - In simplistic terms, saturations reflect O_2 content and is dependant on a balance between consumption and uptake, so when consumption is greater than uptake (very heavy exercise) we will see a drop in saturations. A drop in O_2 delivery to the muscles means they must revert to the inefficient anaerobic fuel pathways, lactic acidosis will occur and fatigue will develop.

References

West, J.B., 2000, *Respiratory Physiology – The Essentials*, 6th ed, Lippincott Williams & Wilkins

Lumb, A.B., *Nunn's Applied Respiratory Physiology*, 5th ed, Butterworth Heinemann

Ganong, WF, 1999, *Review of Medical Physiology*, 19th ed, Lange