Ventilation volume and PIAF when wearing Negative and Positive Pressure Respirators

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Introduction

When writing standards for RPE (Respiratory Protective Equipment), it is most important to have the main objective clearly understood. The main objective is, as I understand it, to protect people who have to work in environments containing hazardous gases or particulates or both.
The most important task, then, is to get those people to wear the RPE 100% of the time they spend in that environment.
The second most important task is that the equipment performs as expected (filtering performance, air supply, maintain positive pressure, etc).
There are other important aspects of a functional RPE program, but in this document we will focus on those two only.
To get someone to wear a respirator 100% of the time requires that the RPE must not cause any hindrance to the user in doing his or her task. This includes both physiological and psychological restrictions.
I will focus on breathing resistance and how that will influence the performance in regard to protecting the wearer.
There have been many papers published over the years touching on this subject, the first and possibly the most often quoted being that of L. Silverman.(8) As we know, he did a lot of physiological studies after World War II, and a lot of our standards are somewhat based on his research.
However, I believe we have not followed his recommendations with regard to how to test RPEs.
When we listen to the response from all those First Responders and other personal attending to the 9/11 incident,(2) there was a clear message saying: we can't wear those respirators *and* do what we have to do.
With this background, we at SEA decided to try to sort this out, at least so that we could understand the issue better.

The test program

Using a Monark 839E Ergomedic Test Bicycle connected to a computer, a test protocol was developed using the software supplied with the test bicycle.
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 trough the respirator was measured, as well as PIAF (Peak Inhalation Air Flow) using a flow/volume meter based on pressure-drop change over a known resistance.
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). A traditional impeller will not be fast enough to record this. The downside is that the pressure drop over a known resistance is not linear. There are a number of ways to overcome this, calibrating the equipment at a number of flows, and so on. For this test, however, 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. We then correlated the performance above and below as shown in the following table.
The flow meter was calibrated at 200 liters and, being non-linear, had the following errors (that were ignored) at other flow rates:

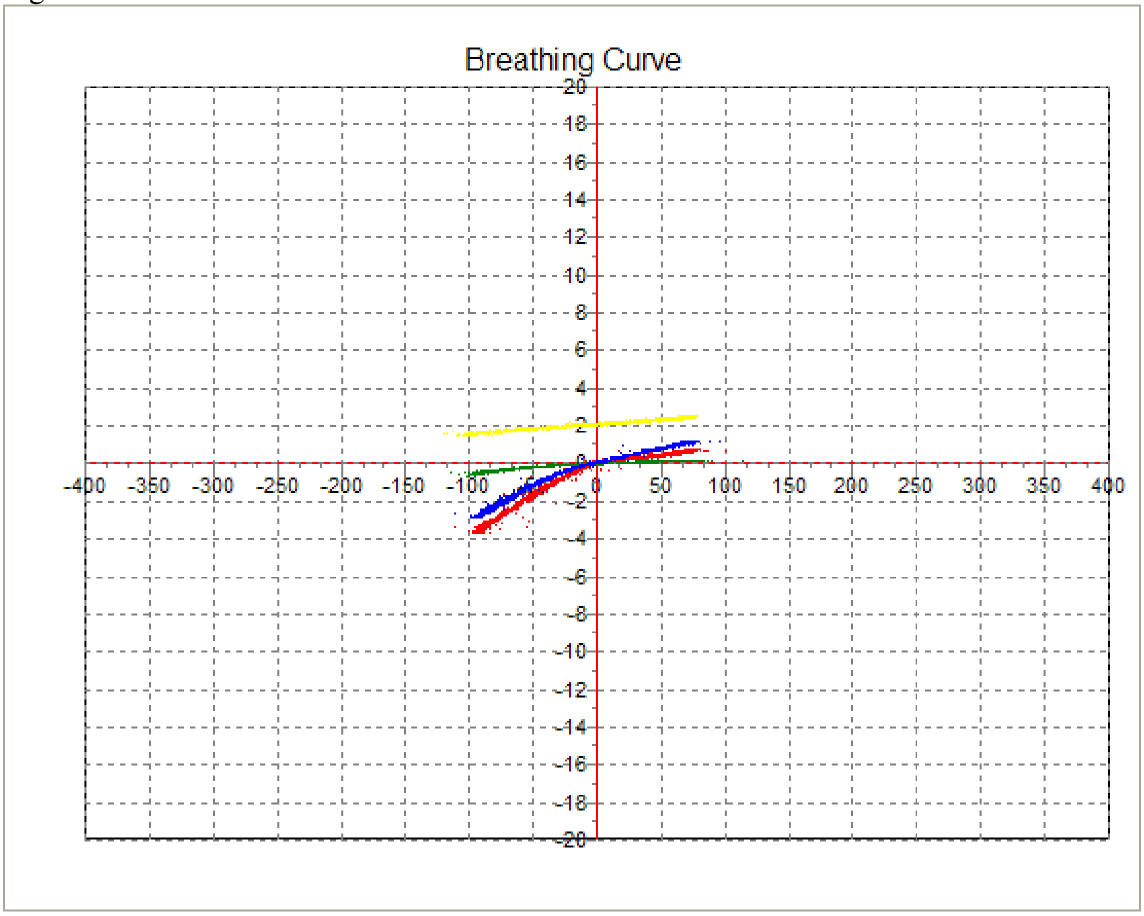
True flow (liters)	Measured flow (liters)	% error
400	472	+18
300	342	+14
200	201	±0
175	162	–7.5

This information was sent to SEA-developed EDL (Extended Data Logging) software for analysis.
The five minutes at each level of work where conducted as follows:
The first three minutes: pedaling the bike with no talk to establish a stable heart rate, measuring and recording the %SpO_2.
The fourth minute: reading out loud as when talking normally. We used the text applied in testing RPEs in Australia as well as Europe: "*When the sunlight strikes raindrops in the air [...]*". This reading was repeated for one minute.
After the fourth minute we let the subject pedal for the remaining minute before the program automatically increased the resistance by 25 W.
The sequence was then repeated, over and over again, until we either reached forty minutes or 85% of max heart rate, as explained above.

Equipment tested
We used four different RPEs; the aim was to get a range of resistance both for inhalation and exhalation.
A Sundstrom-produced full face mask with only the filter used for the flow measurement was used as low resistance with a pressure drop of 7mm water column at 85 liters/min for inhalation and a pressure drop of 2mm water column at 85 liters/min 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 35mm water column at 85 liters/min for inhalation and a pressure drop of 8mm water column at 85 liters/min exhalation.
The third RPE was an M40 with an M42A1 military filter and the flow meter with a pressure drop of 30mm water column at 85 liters/min for inhalation and a pressure drop of 12mm water column at 85 liters/min exhalation.

The fourth RPE was an SEA SE400. We used only the flow meter as the filter, as the performance of this equipment is independent of the pressure drop over the filter, with a pressure drop of 0mm water column at 85 liters/min for inhalation, and a pressure drop of 23mm water column at 85 liters/min exhalation.

Fig. 1



Pressure drop in mbar and flow in liter a breathing machine: 2.05 liters by 14 strokes per minute.

M40 Blue
SEA F/F Read
SE400 Yellow
SR200 Green

Results

As has been written by many authors(8.9.10) of research before me, it is absolutely clear that a human can breathe very high volumes at very high PIAFs.

The spreads of both volume and PIAF were large (average minute volume 24.8 l/min—132.2 l/min and PIAF 50 l/min (0.8333 l/sec)—600 l/min (10 l/sec)). This indicates that the capability of different people's breathing through an RPE is very different depending on both physical size, fitness and willingness to withstand the added load and added discomfort caused by the resistance.

"*A man who knows that he will not see his wife and family again unless he wears a respirator will tolerate much higher pressure drop than, say, a miner who is told that if he wears a dust mask on every shift for the next 10–20 years, his chances of developing pneumoconiosis will be reduced*."

(modified quote from Cotes: *Physiological Aspects of Respirator Design*.)

The heart rate was linear to the workload, independent of the breathing resistance. This is what we expected. [1,9] The result could be different if the test subjects were dressed in working clothes instead of shorts and t-shirts, as that would interfere with the body's heat exchange.

The %SpO_2 — per cent oxygen saturation in the blood — was between 99%-91%. 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 *Oxygen Consumption and Delivery Summary* by Dr Billy M. Drew).

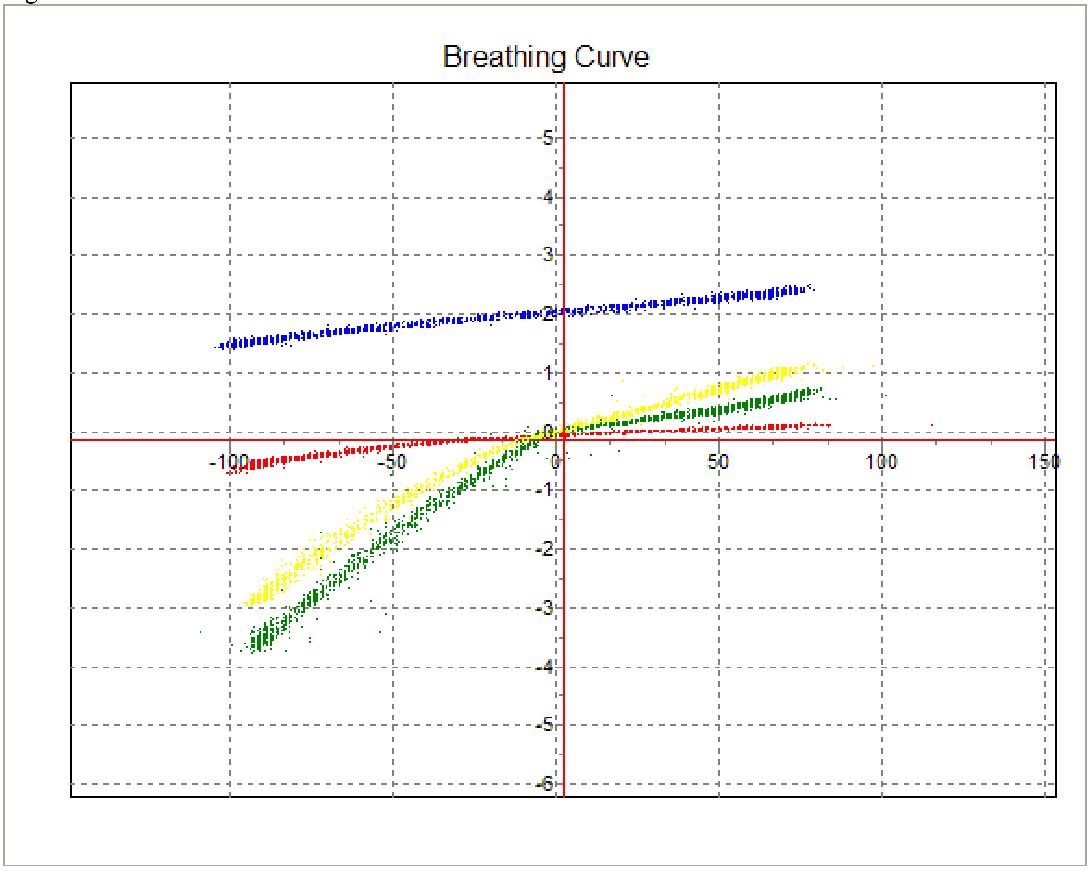
We tested the respirator with a breathing machine at two lung volumes and four revolution rates to calculate the different level of energy required to just breathe through the respirator.

We did not recalibrate the test bench, as it was recently calibrated and, when checked against calibrated flow meters, we were within acceptable tolerances of ±15%.

On the graph below, the horizontal values are PIAF measured in liters per minute, and the vertical is the pressure drop in millibar.

The RPE used had the following data in regards to work load @ 2.05 liters and 14 strokes per minute.

Fig. 1a

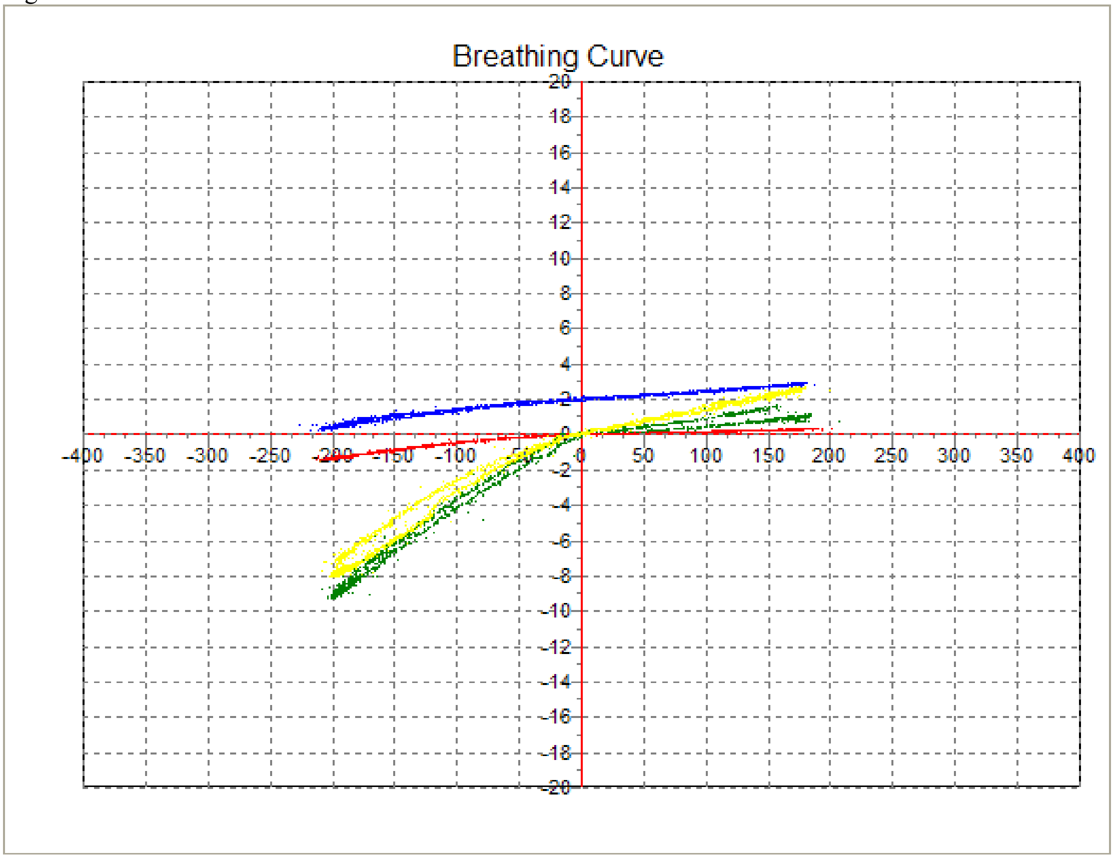


	Inhalation work load in			Exhalation work load in			Total work load in			
	Joule per Breath	**Calories per Breath**		**Joule per Breath**	**Calories per Breath**		**Joule per Breath**	**Calories per Breath**	**Joule per Minute**	**Watt Minute per Minute**
2.05 liters * 14 strokes										
SR200	0.1166	0.0278		0.0152	0.0036		0.1318	0.0315	1.845	0.031
SEA F/F	0.6491	0.1549		0.1277	0.0305		0.7768	0.1854	10.875	0.181
M40	0.4943	0.118		0.1444	0.0345		0.6387	0.1524	8.942	0.149
SE400	0	0		0.3462	0.0826		0.3462	0.0826	4.847	0.081

The above graph (fig. 1a) represents the rate we use for testing and approving respirators in both US, CE and Australia. At this low work rate, both the inhalation and exhalation curves are almost linear.

The RPE used had the following data in regards to work load @ 2.65 Liter and 23 strokes per minute.

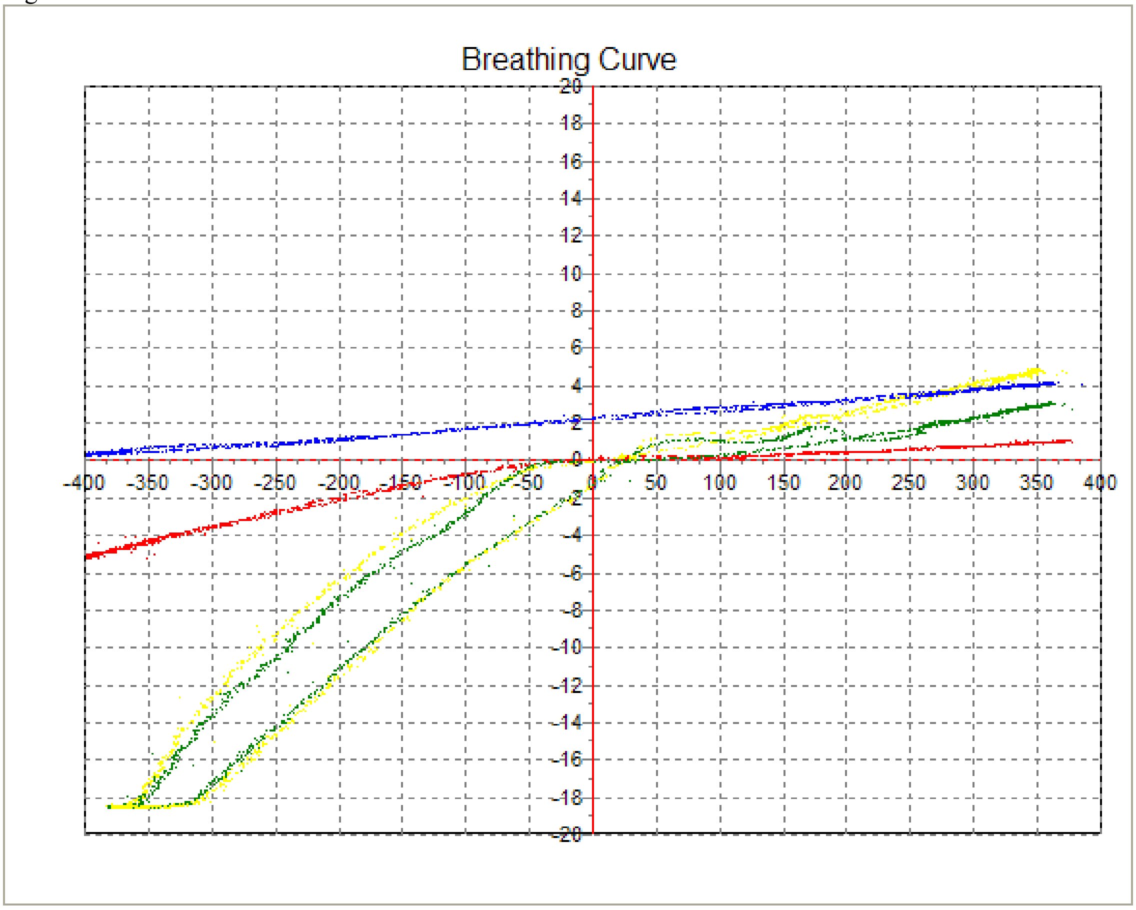
Fig. 2



	Inhalation work load in			Exhalation work load in			Total work load in			
	Joule per Breath	Calories per Breath		Joule per Breath	Calories per Breath		Joule per Breath	Calories per Breath	Joule per Minute	Watt Minute per Minute
2.65 liters * 23 strokes										
SR200	0.3417	0.0816		0.0582	0.0139		0.4	0.0955	9.200	0.153
SEA F/F	2.0613	0.492		0.2839	0.0678		2.3452	0.5597	53.940	0.898
M40	1.7601	0.4201		0.5573	0.133		2.3173	0.5531	53.298	0.888
SE400	0	0		0.5433	0.1297		0.5433	0.1297	12.496	0.208

The RPE used had the following data in regards to work load @ 2.65 Liter and 48 strokes per minute.

Fig. 3



	Inhalation work load in			Exhalation work load in			Total work load in			
	Joule per Breath	Calories per Breath		Joule per Breath	Calories per Breath		Joule per Breath	Calories per Breath	Joule per Minute	Watt Minute per Minute
2.65 liters * 48 strokes										
SR200	1.1084	0.2645		0.1902	0.0454		1.2986	0.3099	62.333	1.038
SEA F/F	3.6816	0.8787		0.5584	0.1333		4.24	1.0119	203.520	3.389
M40	3.6308	0.8685		0.8736	0.2085		4.5044	1.075	216.211	3.600
SE400	0	0		0.7811	0.1864		0.7811	0.1864	37.493	0.624

Fig. 3 shows the highest PIAF at which we tested the RPE, as at 350 liters the pressure drop got higher than the range of the transducer. It is likely that the pressure drop passed 20–22 mbar at 400 liters for the M40 and the SEA F/F. As we can see here, there is a big difference between the different RPEs in the exhalation pressure drop.

Data from the test subjects

We had 8 subjects between 17–55 years of age, of various fitness levels (see table).

No-one could continue to a work-load of 225 W and still remain below 85% of theoretical heart rate. We allowed a few to go beyond this level as we were comfortable they had the required fitness level to do that.

I am showing a few graphs of the two extremes, one being a woman of 38 years of age and the other a man of 50 years of age.

Both kept reasonably fit by doing exercises at the gym a few times per week.

Fig. 4

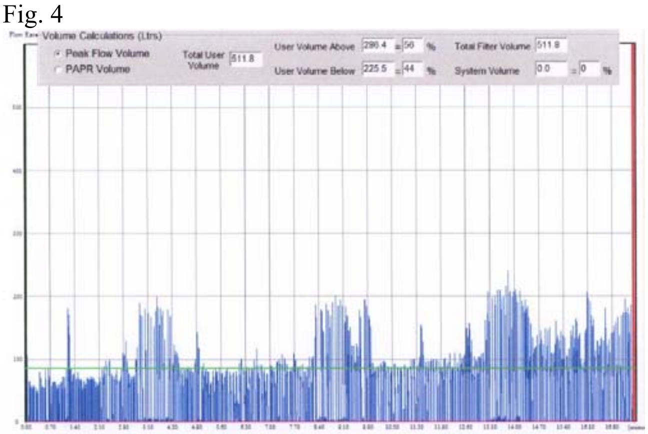


Fig. 4 shows the woman using an SR200 full face mask with only the flow meter consisting of a P100 filter. We can clearly see the 4th minute when the reading occurs. The PIAF reached approximately 235 liters/minute.

Fig. 5

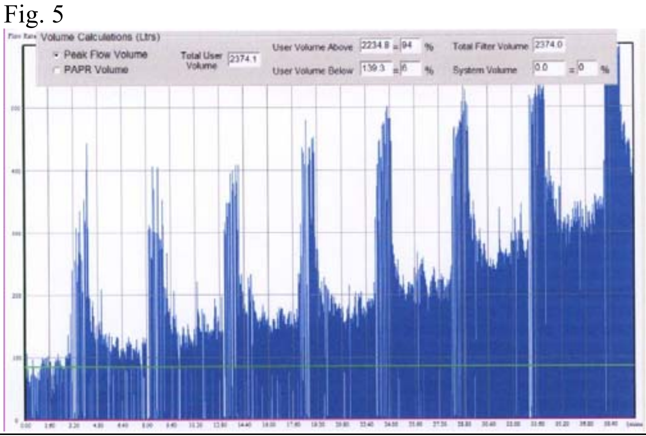


Fig. 5 shows the male also using the SR200 full face mask with only the flow meter. However, this person managed to go to 225W and 40 minutes. At the end the heart rate was on the 92% level. The PIAF here reached approximately 600 liters (see calibration table page2).

Fig. 6

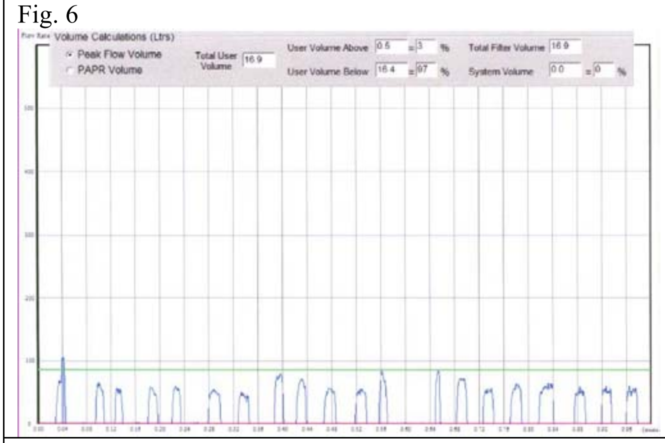


Fig. 6 shows the first minute where only the first breath peaks above 85 liters, the total volume being 16.9 liters over 20 breaths. Fairly light work as far as we are concerned.

Fig. 7

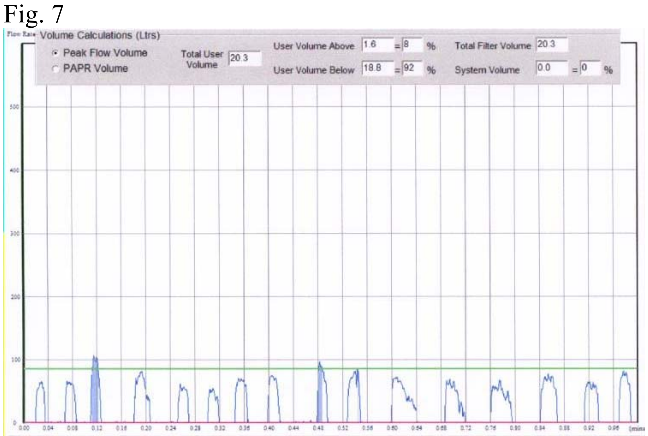
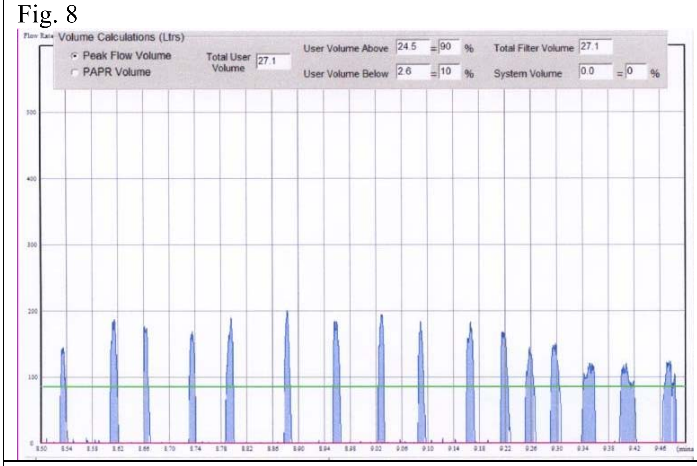


Fig. 7 also shows the first minute where only two breaths peak above 85 liters, the total volume 20.3 liters over 16 breaths.

<table>
<tr>
<td>Fig. 8

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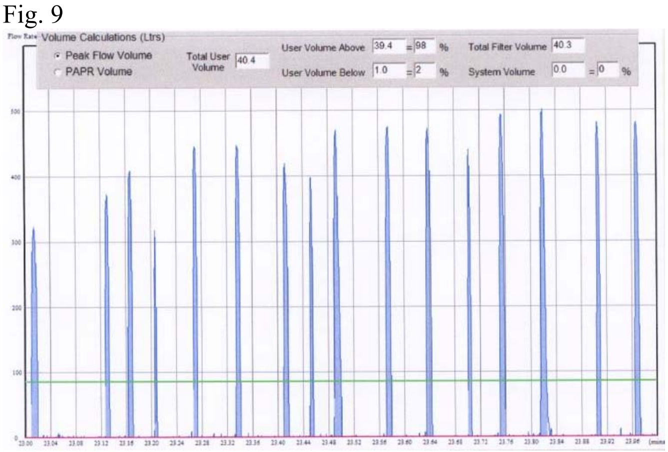
<td>Fig. 9

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<td>Fig. 8 shows the second reading minute, minute 8–9 in the exercise. The external work load required to pedal the bike is now 75W. What is happening here is that the reading aloud is placing priority on the breathing and therefore a reduction in the breath and volume. Total volume of 27.1 liters with all breaths having a peak over 110 liters, the highest being 190 liters of the total volume of 24.5 liters or 90% flowing faster than 85 liters through the filter. The %SpO_2 drops to unhealthy low levels.</td>
<td>Fig. 9 shows the fifth reading minute for the man, minute 23–24 in the exercise. The external work load is now 150W. As with the woman, the reading aloud is placing priority on the breathing. Total volume 40.3 liters with all breaths having a peak over 310 liters with the highest being 500 liters of the total volume of 39.4 liters or 98% flowing faster than 85 liters through the filter. Now the %SpO_2 drops to unhealthy low levels.</td>
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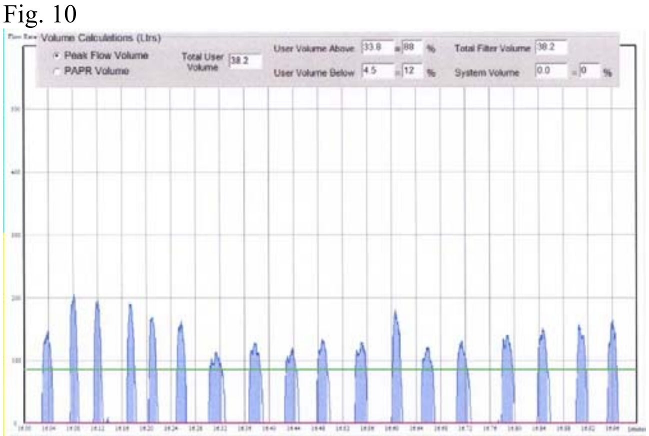
<td>Fig. 10

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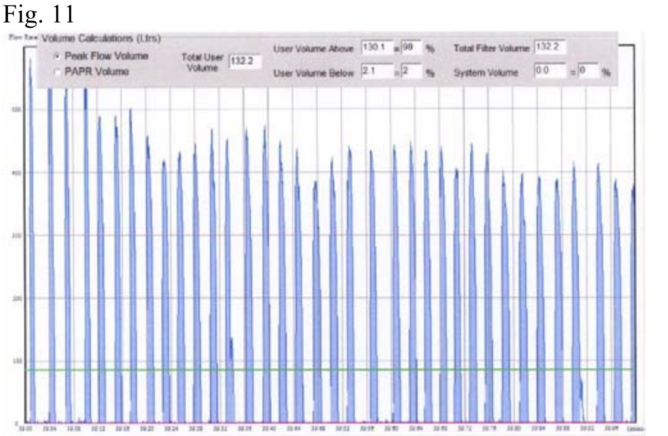
<td>Fig. 11

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<td>Fig. 10 shows the last minute before the test was terminated due to reaching 85% of theoretical maximum heart rate. Total minute volume is 38.2 liters with 33.8 liters or 88% flowing faster than 85 liters. We will discuss the significance of this later in the paper. Only 18 breaths in this minute, which indicates by itself that the woman is not exhausted.</td>
<td>Fig. 11 shows the last minute before the test was terminated due to end of test, i.e. 225W and 40 minutes. Total minute volume is 132.2 liters with 130.1 liters or 98% flowing faster than 85 liters. 36 breaths in this minute, which indicates by itself that the man is close to exhaustion.</td>
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</table>

These two persons are the two extremes. The other test subjects are in between. One thing is very clear: the capability of the breathing system has a wide span and can slow down to very low volumes of air in accordance to the task, and equally go very high if that is what the task requires. There does not seem to be any average number (liters of air breathed or PIAF) applicable to a group of people, nor to a specific task. It all seems to be governed by size, genes, gender and fitness.
Of course, the small sample represented by those graphs is taken with a mask containing two exhalation valves and only a P100 mechanical filter with a large surface area, meaning that the pressure drop is very low during both inhalation and exhalation.
Let's have a look at some samples where we go in the other direction, using a US military mask with NBC filter plus the flow meter.

Fig. 12

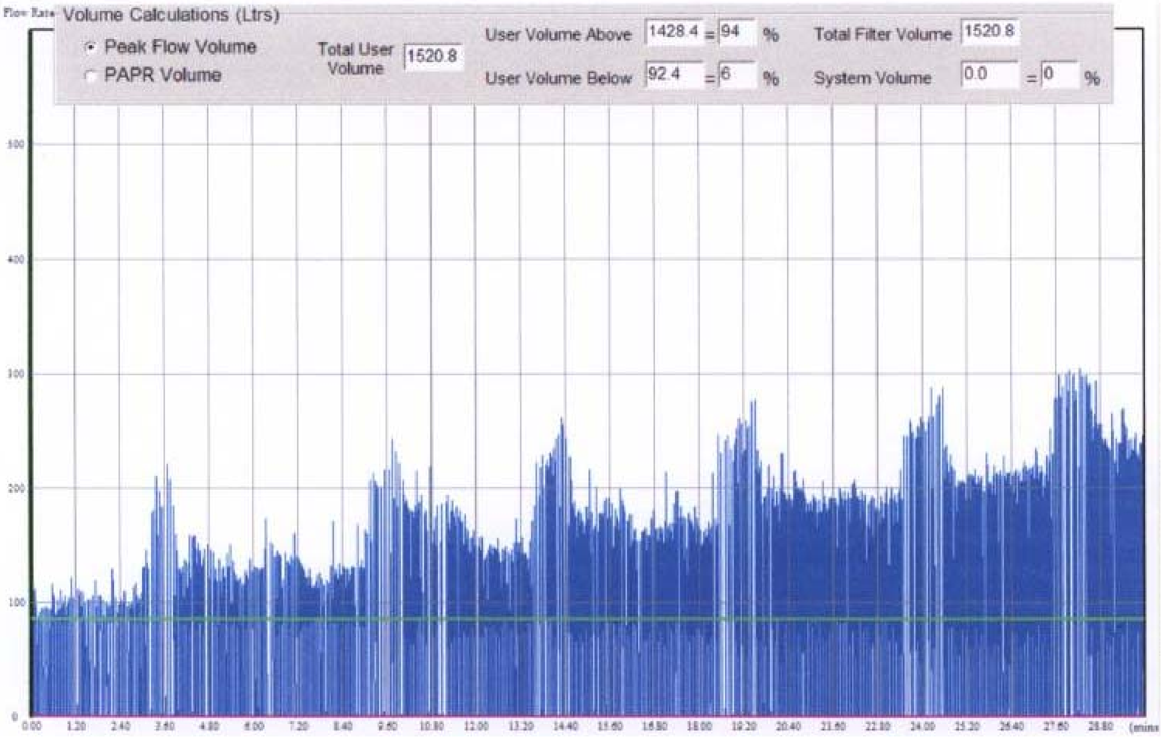


Fig. 12 shows the same man as we looked at before, wearing the SR200 Full Face mask. The pattern is the same, but at a lower PIAF, as the pressure drop has increased dramatically. It is about 3–5 times higher than the other mask/filter combination. This test was also discontinued at the 85% level or 145–149 heartbeats. This always occurred after about 30 Minutes or at 175W, as the heart rate is parallel to the external work load.

Let's have a look at the second minute and a minute in the middle (Fig. 13 & 14):
We start with the first minute. External work load is only 50W. What is interesting is the shape of the breathing curve. The total volume here is 32.8 liters/minute, the PIAF 100-120 liters, and if we divide the 120 with the volume we get 3.6585, which is not that far from what we use normally when we estimate PIAF. But remember: this is in the second minute only, and the work load is low. If we go to the 23rd minute which includes speech, the total volume is 43.3 liters/minute and the PIAF is between 250 and 285 liters. 285 divided by 43.3 is 6.5668. This relationship we have seen at all our testing and all our live data logging.

Fig. 13

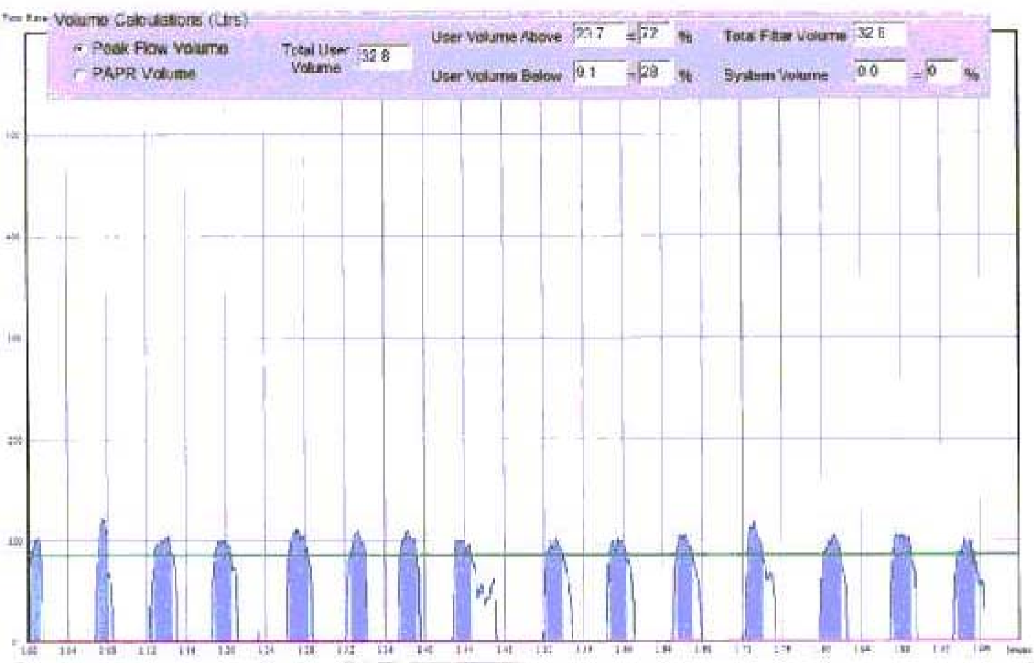
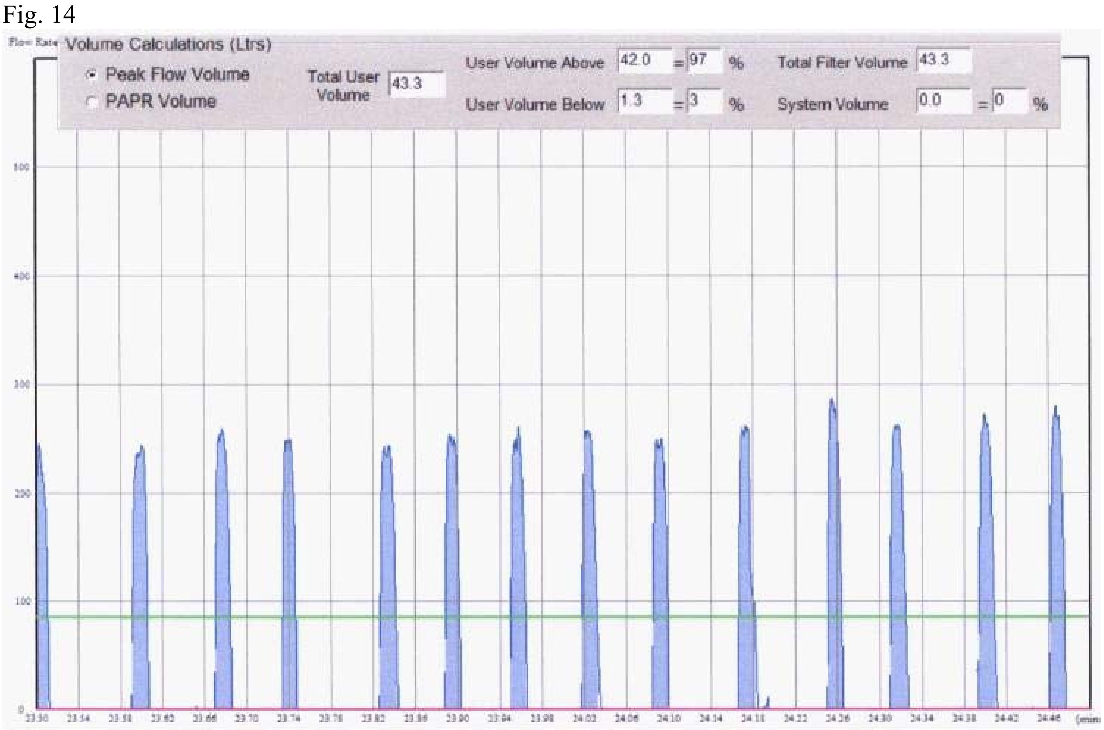


Fig. 14



What does all this mean to all of us who use, manufacture and, last but not least, test and approve RPEs?

Firstly, to me this reinforces what Leslie Silverman and his associates said already in 1943 in their paper, *Fundamental Factors in the Design of Protective Respiratory Equipment.* In his introduction, Silverman says: *"It is well known among Physiologists that during hard work or maximum exertion minute volume of 65 to 100 liters are not uncommon. If these minute volumes should be approached in the actual use of* *protective devices, the present standards would not provide a satisfactory basis on which to evaluate protection."*

However, not all of his conclusions are correct. He claims for example that the pressure drop is linear with the flow, which is not true when it comes to RPE (see the graph on page 7). He also misinterprets what is happening when the flow passes the 85-liter line (see fig. 15); Silverman believed that only the air in the blue-colored area flows faster than 85 liters. This is not correct: the base axis is the timeline and, in this case, going from right to left, the first green field is the acceleration of *all* air up to 85 liters flow. When the flow passes 85 liters, *all* of the air colored red *and* blue flows faster than 85 liters. It is a mistake to think that some air flows slower, and some faster. Then the decelerating curve passes the 85 liter flow (the second green-colored area), when all the air flows slower again. As you can see, this makes a very big difference to the assumptions of how much air is actually flowing at a speed above 85 liters per minute.

Fig. 15

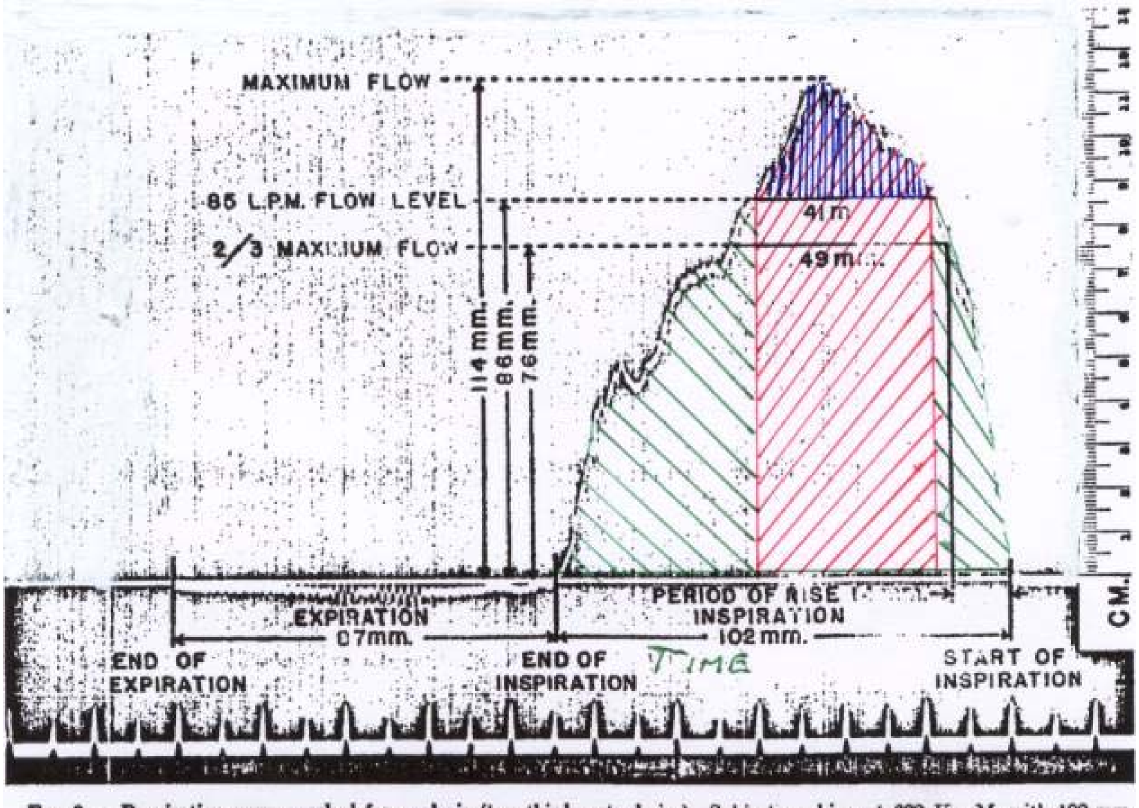


FIG. 9. — Respiration curve marked for analysis (two-thirds actual size). Subject working at 622 Kg. M. with 102 mm. inspiratory resistance. The maximum flow is obtained by measuring the maximum deflection — in this case, 114 mm., corresponding in this record to a flow of 112 liters per minute. The sustained flow level is taken as two-thirds of the maximum flow. The period of rise is the distance between the start of inspiration and the point at which a perpendicular from the start of sustained flow crosses the base line — in this case, a distance of 14 mm. in an inspiratory cycle of 102 mm., i.e., 13.7 per cent. The period of inspiration is 102 mm. and the total respiratory cycle, 189 mm., inspiration thus being 54.0 per cent of the total cycle. The sustained flow is maintained for 49 mm., or 48.0 per cent of the inspiratory cycle. The line at 86 mm. represents the 85-liter-per-minute flow level. Flow is maintained above this level for 41 mm., or 40.2 per cent of the inspiratory cycle. Time interval, one-fifth second.

Graph from L. Silverman's 1943 paper.

Lets have a look at some breathing curves with M40 respirators which represent the highest pressure drop in this test.

Fig. 16	Fig. 17

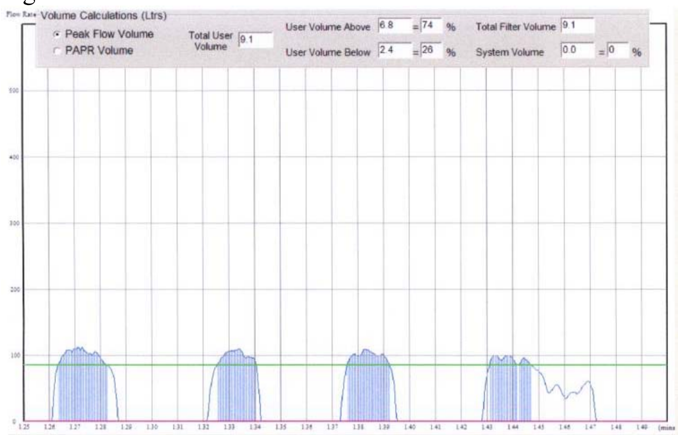
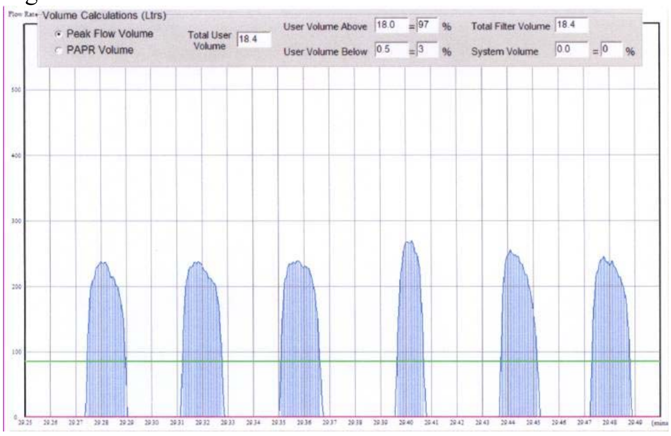

	

Fig. 16 shows 15 seconds of the second minute using the M40 mask. As we can see, the shape of the breathing curve is very similar to what Silverman describes. This is however only at 50W external work load; the volume is 36.4 liter per minute and the PIAF is approximately 110 liters, of which 27.2 liter or 74% of total volume flows faster than 85 liters through the filter.	Fig. 17 shows 15 seconds of the twenty-ninth minute, just after a minute of reading using the M40 mask. As we can see, the shape of the breathing curve is pointier and almost all air, 97%, is flowing faster than 85 liters. The external work load is now 175W; the volume is 73.6 liters per minute.

Fig. 18 (below) shows 15 seconds of the 28th minute while talking. Here we see PIAFs of 300 liters and a minute volume of 62.4 liters, of which 61.2 liters or 98% of total volume of air flows faster than 85 liters through the filter.

The significance of this, in particular, raises the question: how well will the filter cope with high air flow?

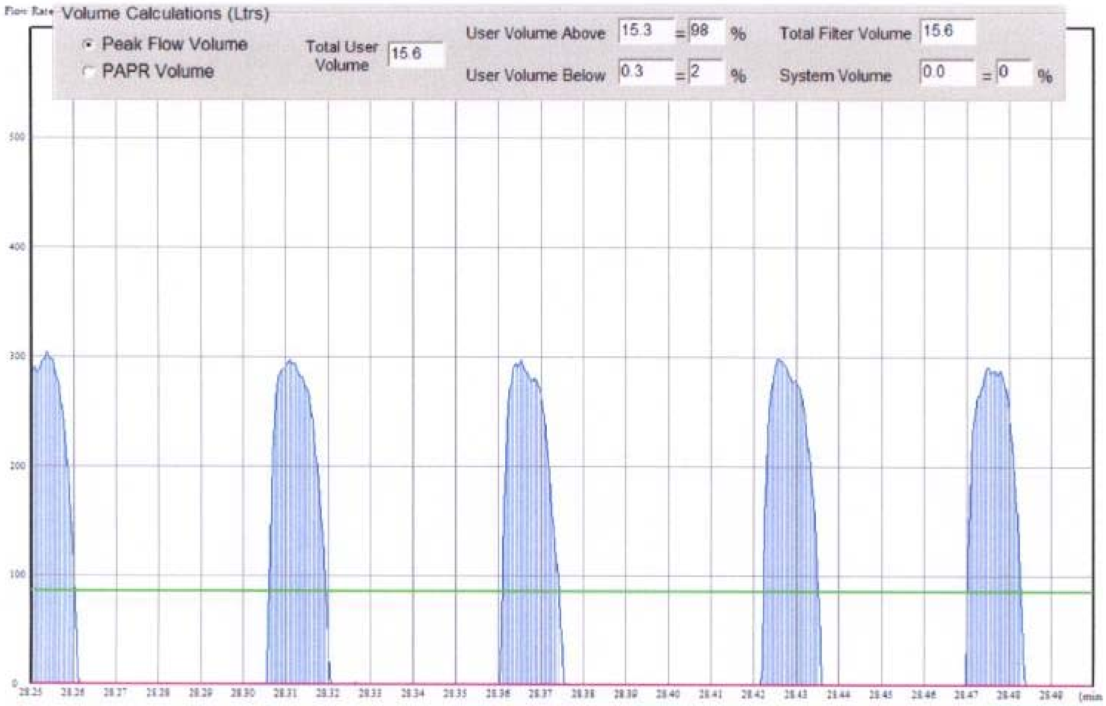
A study by Garry Nelson in the 1960s confirms that the absorption capacity of active carbon in regards to solvents is not significantly effected by air flow. What we don't know is how acids and ammonia are affected by the increased flow.

We know, however, that particulate filters are velocity-dependent, and therefore should be tested at a variety of flow rates, not only to verify penetration but also pressure drop. There are few if any filters with a linear pressure drop as a function of air flow.

Pressure drop has no measurable influence on heart rate. It has, however, an important influence on the capacity of a person to perform a task at the upper level of that person's work rate, that is, >80% of maximum capacity.(7)

Silverman too says in his paper that: "*Pulse rate changes are not significantly altered by resistance. They are, however, effected materially by physical condition and adaptation to work.*" (9)

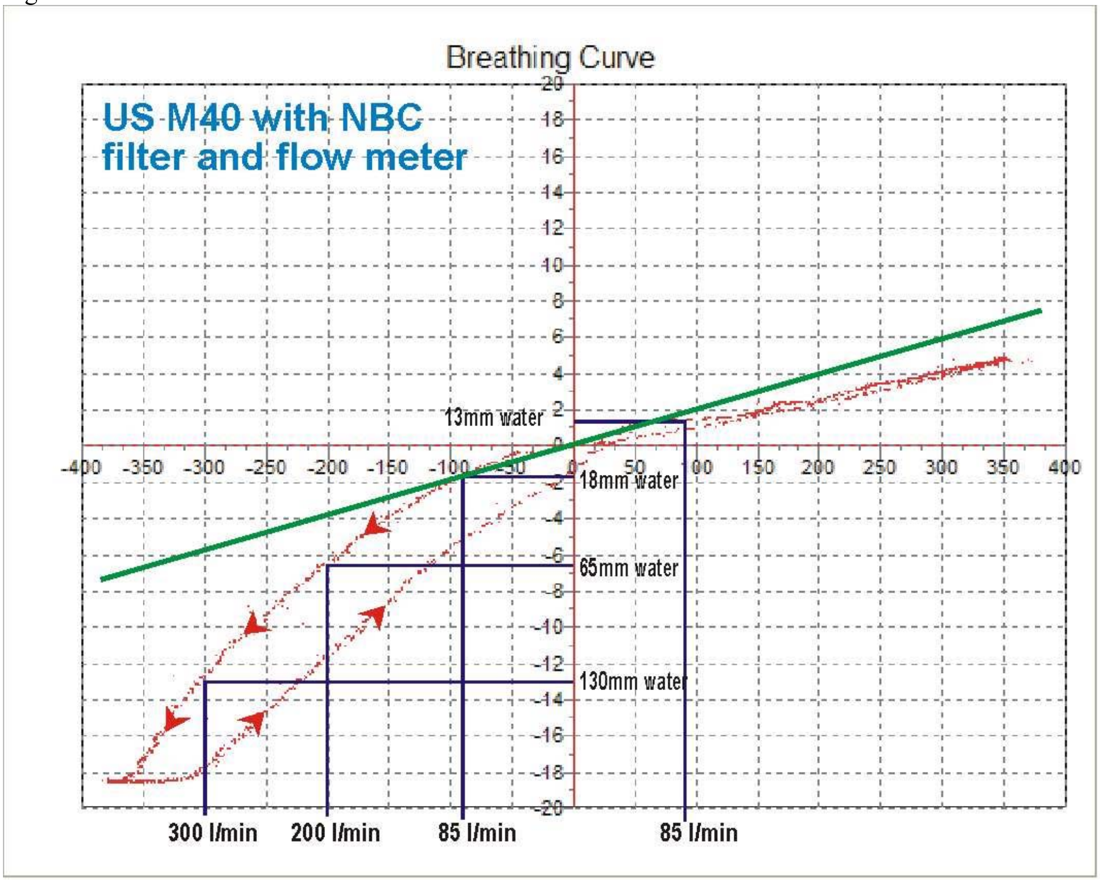
Fig. 18



Work rate and pressure drop

In his early work tests, Silverman used the following work rates:
179 kgm/minute (kilogram metre per minute) = 29W, 415 kgm/min = 68W, 830 kgm/min = 136W and 1107 kgm/min =181W. He recommended a limit to the maximum pressure drop a subject can sustain at 68W. This means that the inhalation pressure should not exceed 106mm water column at 85 liters flow, and exhalation pressure should not exceed 76mm water column at 85 liters flow. This is for 480 minutes of usage: an increase in the pressure drop, as well as work load, will reduce the wear time.
This statement is based on his assumption that pressure drop over the filter is linear with the flow rate, which is not true with the filters we are producing and using today (See fig. 19).

Fig. 19



The work rate Silverman used in his testing is described in fig. 20 below, together with data from *Textbook of Work Physiology* and the EN 27243:1993

Fig. 20

Silver-man			Textbook of Work Physiology		Silverman	EN 27243:1993	
kgm /min	Watts	Joules	Oxygen uptake (l/min)	Heart rate (beats /min)	Perceived work rate	Value to be used for calculation of mean metabolic rate	
					Resting	117	**Resting**
179	29	18	0.5	Up to 90	Very light work no limit	180	**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).
415	68	42	0.5–1.0	90–110	Medium work up to 480 Minute with Pressure drop of <–64mm +41mm @ 85 liters flow	297	**Sustained hand and arm work** (hammering in nails, filling), **arm and leg work** (off-road operation of lorries, tractors or construction equipment); **arm and trunk work** (work with pneumatics hammer, tractor assembly, plastering, intermittent handling of modestly heavy material, weeding, hoeing, picking fruit or vegetables); pushing or pulling lightweight carts or wheelbarrows, **walking at a speed** of 3.5–5.5 km/h or 2.2–3.4 mph; forging.
415	68	42	1.0–1.5	110–130	Medium work up to 75 Minute with Pressure drop of <–106mm +76mm @ 85 liters flow	414	**Intense arm and trunk work**; carrying heavy materials; shovelling; sledge hammer work; sawing, planning or chiselling hard wood; hand mowing; digging; **walking at speed** of 5.5–7 km/h or 3.4–4.4 mph. Pushing or pulling heavily loaded handcarts or wheelbarrows; chipping castings; concrete block laying.
830	136	85	1.5–2.0	130–150	Heavy work up to 75 minutes <–82mm +53mm @ 85 liters flow	522	**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, **walking at a speed** greater than 7 km/h or 4.4 mph.
1107	181	113	Over 2.0	150–170	Extremely hard work up to 15 minutes with Pressure drop of <–64mm +41mm @ 85 liters flow		

Fig. 21

Åstrand work rate table		
Watts	kgm/min	Oxygen uptake, liters/min
50	306	0.9
100	612	1.5
150	918	2.1
200	1224	2.8
250	1530	3.5
300	1836	4.2
350	2142	5
400	2448	5.7
450	2754	
500	3060	

I have compiled the table above (fig. 21) to show that many of previous papers present approximations between metric and imperial expressions using metric units. 1 Watt = 0.102 kgm/second or 6.12 kgm/min.

Data

Below is the data summarized from our test. All subjects completed the first three five-minute sections. The first three minutes had an average minute liter of 36.7 liters, of which 17.7 liters or 48% was flowing faster than 85 liters. This is a very low work load. Still, 48% flows faster than the test flow used to test particle filter penetration, as well as in pressure-drop testing.
This clearly indicates that testing flows must be changed as a matter of urgency. The faster-than-85-liter flow increased to 57% in the fourth minute as we implemented speech as a parameter.
In the third five-minute section, the volume had increased to 55.1 liters, of which 74% flowed faster than 85 liters; and when speech was implemented, this increased to 77%. Moreover, in the recovering minute after the speech, the faster-than-85-liter rate hit 81%. In this third section, the external work load was still only 100W, and the average number of breaths was 26 in the last minute of this section. This does not indicate that the subjects were close to exhaustion.
The fourth section was completed by 5 subjects. The fifth, sixth and seventh sections were completed by four subjects. As the test went on, those numbers just got higher, see fig. 22.

Fig. 22

This test covers 8 test subjects and up to 5 tests per subject. There were 7 males and 1 female.				**First 5 minutes @ 50W with NO talking during the 3 mins, TALKING during the 4th minute, and just pedaling during the 5th minute.**							
	Age	Height (cm)	Weight (kg)	50W (1-3 Min)	Liter faster than 85 liter flow	50W (4 Min)	Liter faster than 85 liter flow	No. of breaths /vol. per breath	50W (5 Min)	Liter faster than 85 liter flow	No. of breaths /vol. per breath
Average	**43.1**	**180.8**	**82.3**	**36.7**	**17.7**	**50.7**	**29.1**	**16.4**	**49.5**	**33.8**	**22.4**
Standard deviation	**11.3**	**8.2**	**12.1**	**16.0**	**12.8**	**42.3**	**12.8**	**3.2**	**21.7**	**15.0**	**6.6**
Avg. volume per breath in the 4th and 5th minute.								3.09			2.21
% flowing faster than 85 liters.					48%		57%			68%	
Avg. liters of air per minute with Negative Pressure RPE				31.0	17.7	37.2	24.6		37.3	29.1	
Avg. liters of air per minute with Positive Pressure RPE				52.3	17.8	87.3	41.0		82.5	46.3	
Avg. no. of breaths per minute with Negative Pressure RPE								16.2			21.1
Avg. no. of breaths per minute with Positive Pressure RPE								17.0			25.9

Fig. 22 (cont.)

This test covers 8 test subjects and up to 5 tests per subject. There were 7 males and 1 female.				**Third 5 minutes @ 100W with NO talking during the 3 mins, TALKING during the 4th minute, and just pedaling during the 5th minute.**							
	Age	Height (cm)	Weight (kg)	100W (1-3 Min)	Liter faster than 85 liter flow	100W (4 Min)	Liter faster than 85 liter flow	No. of breaths /vol. per breath	100W (5 Min)	Liter faster than 85 liter flow	No. of breaths /vol. per breath
Average	**43.1**	**180.8**	**82.3**	**55.1**	**40.9**	**53.5**	**41.1**	**19.5**	**63.8**	**51.6**	**25.7**
Standard deviation	**11.3**	**8.2**	**12.1**	**19.3**	**11.1**	**26.1**	**14.8**	**5.8**	**22.5**	**14.6**	**8.8**
Avg. volume per breath in the 4th and 5th minute.								2.75			2.48
% flowing faster than 85 liters.					74%		77%			81%	
Avg. liters of air per minute with Negative Pressure RPE				44.9	38.4	38.7	36.5		51.9	47.6	
Avg. liters of air per minute with Positive Pressure RPE				82.5	47.4	93.9	53.7		96.1	62.3	
Avg. no. of breaths per minute with Negative Pressure RPE								19.0			24.6
Avg. no. of breaths per minute with Positive Pressure RPE								17.0			25.9

Fig. 22 (cont.)

This test covers 8 test subjects and up to 5 tests per subject. There were 7 males and 1 female.				**Sixth 5 minutes @ 175W with NO talking during the 3 mins, TALKING during the 4th minute, and just pedaling during the 5th minute.**							
	Age	Height (cm)	Weight (kg)	175W (1-3 Min)	Liter faster than 85 liter flow	175W (4 Min)	Liter faster than 85 liter flow	No. of breaths /vol. per breath	175W (5 Min)	Liter faster than 85 liter flow	No. of breaths /vol. per breath
Average	**43.1**	**180.8**	**82.3**	**77.6**	**72.3**	**70.9**	**68.9**	**20.8**	**89.7**	**87.4**	**26.5**
Standard deviation	**11.3**	**8.2**	**12.1**	**14.3**	**8.7**	**28.8**	**27.8**	**3.4**	**23.5**	**24.1**	**5.1**
Avg. volume per breath in the 4th and 5th minute.								3.41			3.38
% flowing faster than 85 liters.					93%		97%			97%	
Avg. liters of air per minute with Negative Pressure RPE				73.9	71.0	62.9	61.2		83.1	80.7	
Avg. liters of air per minute with Positive Pressure RPE				111.4	84.2	143.1	138.1		148.5	147.4	
Avg. no. of breaths per minute with Negative Pressure RPE								21.0			26.8
Avg. no. of breaths per minute with Positive Pressure RPE								19.0			24.0

Conclusion

There is no doubt that our predecessors saw what was required to test RPE. Even when their equipment was primitive compared with the technology of today, Silverman's recommendations were clearly to test at higher air flows. I believe that is the reason we changed the air flow for gas adsorbers and absorbers from 32 to 64 liters in the US. However, the experts of the day made some wrong assumptions: firstly, that the pressure drop over the filter was parallel with the flow (see graph below of a number of full face masks with combination Gas/P100 filters purchased in the United States) and secondly, that the portion of air flowing faster than 85 liters/minute was calculated as only the air above 85 liters on the curve (see fig. 15 above). This contrasts with the reality: it is *all* the air from the baseline to the top of the curve that flows above 85 liters/min (again, see fig. 15).
We need to correct those two incorrect assumptions as a matter of urgency, in order to avoid some very serious consequences.

Recommendations

- Particle filters should be tested for penetration not only at 85 liters/minute, but also at 150, 200, 250, 300 and 350 liters' flow.
- Complete RPEs should be tested for pressure drop not only at 85 liters, but at 150, 200, 250, 300 and 350 liters' flow as well.
- RPE should be classified for different work loads representing different tasks, as described in fig. 23.
- A physiologically acceptable number should be found, based on Silverman's and others' research. As Arthur Johnson says in his paper,[6] any resistance will reduce the capability of a person performing a task when that person has to work at his >80% capacity, based on heart rate. Therefore, the goal for manufacturers is to minimize the pressure drop as far as possible.

The sample in fig. 23 is an initial suggestion. This is going to be a compromise, as Arthur Johnson writes in his paper. When pressure drop goes down, PIAF goes up, and the life span of filter absorbers gets shorter. However, for long-term work we cannot allow a high pressure drop if we expect people to keep their RPEs on at all times.
The data to support this increased flow rate is well documented by earlier authors,[8,9,10] as well as in this study (see fig. 24 and 25). We are still collecting data, and should be able to get more data at the higher workload soon as we are getting more subjects to do the fit test.
There is already a lot of data. I have provided a break-up of the readings in the highest, lowest and 'average' PIAF measurements.
It is not right, in my opinion, to talk about 'averages' when it comes to PIAF, as PIAF is so important for both filter penetration as well as pressure drop. If the pressure drop is too high, the person wearing the RPE will simply not sustain a high work load. This is a fact.
Therefore, we can not allow a high pressure drop in RPEs that we expect people to wear for extended periods of time.
We also found in our tests that for many test subjects, 80% of theoretical max heart rate was reached at quite modest work loads.
Of course, the need to be physically fit was identified in early papers,[6] and fitness is a must for people required to wear RPEs for extended periods of time.
I hope this paper helps to clarify this very important issue.

Göran Berndtsson
CEO, The SEA Group.

Fig.23

Proposed NEW test criteria.	External work rate		*Textbook of Work Physiology*		**EN 27243:1993**	
Acceptable Pressure drop @ flow rate.	Watts	Joules	Oxygen uptake (l/min)	Heart rate (beats/min)	Value to be used for calculation of mean metabolic rate	
50 mm water column @ 85 liter/minute					117	**Resting**
80 mm water column @ 150 liter/minute	30	19	0.5	Up to 90	180	**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 miles/h).
100 mm water column @ 250 liter/minute	60	37	0.5-1.0	90-110	297	**Sustained hand and arm work** (hammering in nails, filling), **arm and leg work** (off-road operation of lorries, tractors or construction equipment); **arm and trunk work** (work with pneumatics hammer, tractor assembly, plastering, intermittent handling of modestly heavy material, weeding, hoeing, picking fruit or vegetables); pushing or pulling lightweight carts or wheelbarrows, **walking at a speed** of 3.5-5.5 km/h or 2.2-3.4 miles/h; forging.

Proposed NEW test criteria.	External work rate		*Textbook of Work Physiology*		**EN 27243:1993**	
80 mm water column @ 250 liter/minute	75-100	46-62	1.0-1.5	110-130	297	**Sustained hand and arm work** (hammering in nails, filling), **arm and leg work** (off-road operation of lorries, tractors or construction equipment); **arm and trunk work** (work with pneumatics hammer, tractor assembly, plastering, intermittent handling of modestly heavy material, weeding, hoeing, picking fruit or vegetables); pushing or pulling lightweight carts or wheelbarrows, **walking at a speed** of 3.5-5.5 km/h or 2.2-3.4 miles/h; forging.
80 mm water column @ 300 liter/minute	100-150	62-93	1.5-2.0	130-150	414	**Intense arm and trunk work**; carrying heavy materials; shovelling; sledge hammer work; sawing, planning or chiselling hard wood; hand mowing; digging; **walking at speed** of 5.5-7 km/h or 3.4-4.4 miles/h. Pushing or pulling heavily loaded handcarts or wheelbarrows; chipping castings; concrete block laying.
80 mm water column @ 350 liter/minute	150-200	93-124	Over 2.0	150-170	522	**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, **walking at a speed** greater than 7 km/h or 4.4 miles/h.

Fig. 24

	First 5 minutes @ 50W with the first 3 minute NO speech the 4th minute speech and the 5th minute just pedaling.			Second 5 minutes @ 75W with the first 3 minute NO speech the 4th minute speech and the 5th minute just pedaling.			Third 5 minutes @ 100W with the first 3 minute NO speech the 4th minute speech and the 5th minute just pedaling.			Fourth 5 minutes @ 125W with the first 3 minute NO speech the 4th minute speech and the 5th minute just pedaling.		
	The Highest PIAF in 1-3 min.	The Highest PIAF in 4th minute.	The Highest PIAF in 5th minute.	The Highest PIAF in 1-3 min.	The Highest PIAF in 4th minute.	The Highest PIAF in 5th minute.	The Highest PIAF in 1-3 min.	The Highest PIAF in 4th minute.	The Highest PIAF in 5th minute.	The Highest PIAF in 1-3 min.	The Highest PIAF in 4th minute.	The Highest PIAF in 5th minute.
Highest PIAF	270	370	310	315	500	310	270	500	320	315	540	400
Lowest PIAF	105	130	110	115	140	90	130	170	140	140	240	200
Average of the highest PIAF with Negative Pressure RPE	161	226	182	183	267	211	208	296	218	224	366	267
Average of the highest PIAF with Negative Pressure RPE SR200	178	285	205	193	331	240	218	350	235	247	428	282
Average of the highest PIAF with Negative Pressure RPE SEA F/F	149	203	163	172	220	183	187	263	200	195	326	265
Average of the highest PIAF with Negative Pressure RPE M40	147	199	166	181	223	200	216	250	211	213	260	228
Highest PIAF with Negative Pressure RPE	270	370	310	315	500	310	260	500	320	310	540	400
Lowest PIAF with Negative Pressure RPE	105	130	110	115	140	90	130	170	140	140	240	200
Average of the highest PIAF with Positive Pressure RPE	180	254	192	201	268	227	223	281	245	244	306	301
Highest PIAF with Positive Pressure RPE	240	315	240	260	310	280	270	340	305	315	360	340
Lowest PIAF with Positive Pressure RPE	110	200	160	130	200	160	180	230	190	150	240	250

Fig.25

	Fifth 5 minutes @ 150W with the first 3 minute NO speech the 4th minute speech and the 5th minute just pedaling.			**Sixth 5 minutes @ 175W with the first 3 minute NO speech the 4th minute speech and the 5th minute just pedaling.**			**Seventh 5 minutes @ 200W with the first 3 minute NO speech the 4th minute speech and the 5th minute just pedaling.**			**Eighth 5 minutes @ 225W with the first 3 minute NO speech the 4th minute speech and the 5th minute just pedaling.**		
	The Highest PIAF in 1-3 min.	The Highest PIAF in 4th minute.	The Highest PIAF in 5th minute.	The Highest PIAF in 1-3 min.	The Highest PIAF in 4th minute.	The Highest PIAF in 5th minute.	The Highest PIAF in 1-3 min.	The Highest PIAF in 4th minute.	The Highest PIAF in 5th minute.	The Highest PIAF in 1-3 min.	The Highest PIAF in 4th minute.	The Highest PIAF in 5th minute.
Highest PIAF	370	515	430	425	530	480	340	560	430	350	600	500
Lowest PIAF	190	285	215	210	300	270	340	560	430	350	600	500
Average of the highest PIAF with Negative Pressure RPE	245	389	300	296	400	331	340	560	430	350	600	500
Average of the highest PIAF with Negative Pressure RPE SR200	260	451	332	333	448	370	340	560	430	350	600	500
Average of the highest PIAF with Negative Pressure RPE SEA F/F	223	350	278	232	353	287						
Average of the highest PIAF with Negative Pressure RPE M40	240	293	253	300	300	270						
Highest PIAF with Negative Pressure RPE	370	515	430	425	530	480	340	560	430	350	600	
Lowest PIAF with Negative Pressure RPE	200	285	215	210	300	270	340	560	430	350	600	
Average of the highest PIAF with Positive Pressure RPE	248	340	308	220	305	320						
Highest PIAF with Positive Pressure RPE	305	380	310	220	305	320						
Lowest PIAF with Positive Pressure RPE	190	300	305	220	305	320						

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Appendix.

Oxygen Consumption and Delivery

Summary

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Oxygen Consumption and Delivery

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 ∴ 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)
    - ∴ 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?

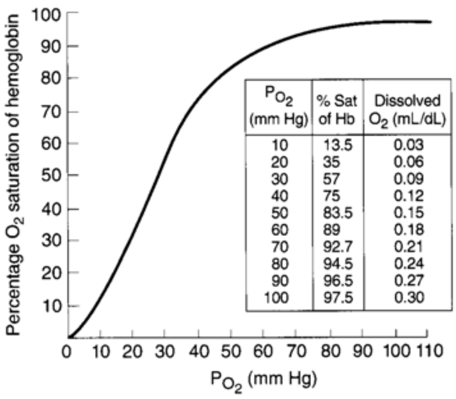
The delivery of oxygen to the tissues is dependent on cardiac output which is normally 5 l/min but can increase to 25 l/min in severe exercise (i.e. 5 times)

- 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



P_{O_2} (mm Hg)	% Sat of Hb	Dissolved O_2 (mL/dL)
10	13.5	0.03
20	35	0.06
30	57	0.09
40	75	0.12
50	83.5	0.15
60	89	0.18
70	92.7	0.21
80	94.5	0.24
90	96.5	0.27
100	97.5	0.30

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.

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