A New Simplified Technique for Measuring Inspiratory Flow Characteristics

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ABSTRACT

Filter penetration is an important factor in determining protection provided by a respirator to workers. However, filter performance is still tested at flow rates based on flow rate data collected in the 1940s which where limited to the technologies available at the time. To accurately chart the human breathing cycle when wearing a respirator, it is important, to achieve readings with as high a resolution as possible. Since the inspiratory airflow in human breathing reaches its peak very rapidly, particularly in conjunction with speech (Holm'er 2003), a true breathing curve can only be generated by an instrument capable of sampling the airflow almost instantaneously.

With the aim of achieving high resolution readings, a simplified type of flow meter was designed for measuring the inspiratory airflow characteristics in humans at a rate of fifty times per second (50 Hz). This paper describes the design of the new simplified flow meter, its construction, its calibration, and the continuous monitoring and verification of its performance.

Subsequent to data collection, the raw flow meter readings were corrected to true flow rates using a regression equation derived from the calibration data.

Keywords: inspiratory flow, breathing cycle, flow meter, resistance, airflow, pressure drop

INTRODUCTION

Respiratory protection has in the past few years become a more prominent issue highlighted by emerging pathogens and chemical, biological, radiological and nuclear (CBRN) agents. Respirator users therefore require the highest possible levels of protection. Face seal leakage and filter penetration are the two main sources of respirator leakage (Chen and Huang, 1998; Hinds *et al*., 1987). The protection offered to the wearer by the respirator is highly dependent on the filter performance. However, filter performance is still tested at flow rates based on flow rate data collected by Silverman *et al*. (1943).

When that early research took place, there were no computers with a clock speed high enough to record and correct the data. Silverman's method used a platinum filament that was inserted into the airflow and photographed. The greater the airflow, the more the filament bent. The degree of the bend was used as an indication of the flow rate. Although this method involved a great deal of lag in the system and had error rates of up to 35% at flow *rates* between 75 and 200 liters per minute, it was ground breaking considering the technology available at the time (Silverman *et al*., 1943).

In order to obtain an accurate picture of the nature of the human breathing cycle when wearing a respirator, it is important to achieve readings with as high a resolution as possible (Lafortuna *et al*., 1984). 'Resolution' in this sense means frequency and accuracy of readings. Since the inhalation airflow in human breathing reaches its peak very rapidly, particularly in conjunction with speech, a true breathing curve can only be generated by an instrument capable of sampling the airflow almost instantaneously. This applies in particular to the capability to record breathing rates in real work situations. Thus, it was necessary to design and build a new type of flow meter.

One major prerequisite for the new flow meter was to add as little as possible to the inhalation resistance that the masks and filters already imposed on the test subject. Only the inhalation phase of the breathing cycle was of interest in this exercise, as the inhalation phase affects face seal leakage and filter performance in both particle and gas filters, and it also plays an important role in the physical performance of the human body due to the added work load caused by increased breathing resistance (Johnson *et al.,* 1999).

One of the challenges encountered in earlier studies has been the limitations of the test equipment, as Silverman *et al.* (1943) pointed out:

"The instrument should be able to measure air flows from 0 to 300 liters per minute"

"It should respond practically instantaneously, without lag or appreciable inertia." (There will always be some additional resistance.)

"The instrument should be, if possible, linear." (Today this can be achieved through electronics.)

"The instrument should be accurate to within 5%." (This is not as important as knowing what the range of accuracy is.)

This paper describes the design of the new flow meter, its construction, its calibration, and the continuous monitoring and verification of its performance. In a companion paper, findings made by this flow meter are discussed (Berndtsson, 2003).

MATERIALS AND METHODS

A new device or data acquisition system (subsequently called flow meter) was developed to measure inspiratory flow. The flow meter was made up of a sensor probe in an empty canister, a pressure transducer, electronics, personal computer, and software. The description of different components is as follows.

The Sensor Probe

Modification to the respirator was not a good option, as a prerequisite was that the device should be applicable to as many different respirators as possible. Accordingly, a modular test adapter was designed by installing the pressure probe in an empty filter canister. A class P100 particle filter was attached to the front of this canister. This solution is expected to achieve maximum consistency. The filter-probe assembly was then attached to the full face mask through an adapter with an M40 respirator thread (EN148-1:1999). The assembly could also be attached to the front of any 'real', unmodified filter (with an approximate diameter of 100 mm) such as a gas cartridge. This combined assembly was then threaded onto the full face mask. Such an assembly is illustrated in Figure 1.

All respirators used in this study relied on facial seal, and featured both inhalation and exhalation valves. The flow meter recorded only the inhalation phase. This was not considered to be a significant issue. If the transducer had been located inside the mask, the airflow measured would no longer be of a one-directional nature. In other words, the flow meter would not give a simple one-way flow indication. To measure exhalation with a simple pressure transducer, an additional fixed exhalation resistance would have to be added. This was seen as an unwanted complication.

The solution used in this flow meter simplified the selection of the pressure transducer, as the airflow was only measured in one direction (*i.e.*, inhalation), and only went in the reverse direction during the very brief time it takes for the inhalation valve to close.

Figure 1. Flow meter sensor probe (From front to back: P100 filter, sensor in empty canister, gas filter, face mask).

The Pressure Transducer

A pressure transducer was an essential component of the device. The flow meter was based on simple flow dynamics stemming from the relationship between the airflow over a fixed resistance and the pressure on either side of the source of that resistance. To create a fixed resistance, a class P100 particle filter was used. This filter had low resistance (approximately 1 mbar at 85 L/min flow, NIOSH maximum allowable resistance at 85 L/min are 5.098577 mbar = 50 mm H_2O) and, when tested, generated a relatively flat resistance vs. flow curve (see Figure 2).

The breathing resistance of a typical Full Face respirator with combination particulate/gas filters produced a pressure drop in the range of 0 to 20 mbar for a flow of up to 500 liters per minute (based on in house testing of wide rage of respiratory protective devices). Accordingly, a pressure transducer suitable for this range was sourced (Silicone Microstructure Inc. SMI5552-003, the maximum pressure: 0.3 psi (20.6843 mbar), sensitivity at 10V power supply: 25mV for Full Scale). The linearity of the transducer, although desirable, was considered to be less important since this factor was easily compensated for using computer software. Accuracy and rapid response were the most important factors in order to ensure that comparable results could be derived from multiple readings of the constantly changing airflow of human breathing.

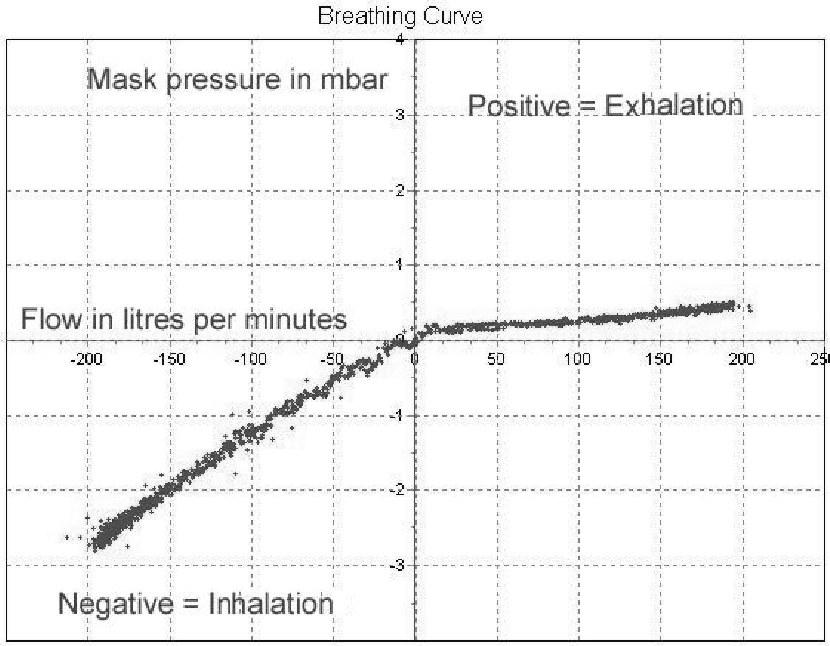

Figure 2. Illustration of the breathing curve from the IPZ breathing machine, *i.e.*, PIAF against pressure drop in mbar.

The Electronics and Personal Computer

The pressure transducer was connected to a circuit board together with an amplifier, an analogue-to-digital converter, and an RS232 transmitter. This assembly, shown in Figure 3, was powered by a battery or external power source. The connection from the pressure transducer to the pressure probe was by means of a piece of tubing. The device is capable of reading the value of the pressure transducer fifty times per second and transmitting this value through the RS232 connection.

Two versions of this flow meter have been produced. One model (the ‘stationary flow meter’) features an analogue interface card for a personal computer, performing both the analog-to-digital conversion and data collection. The other model (the ‘portable flow meter’) features a battery operated palm computer that collects the data, thus making the unit fully portable.

The Software

A program called SE EDL (Extended Data Logger) was developed in house to operate the flow meter. The data were recorded onto a personal computer, either in real-time directly through the interface card of the stationary flow meter, or by downloading all the collected data from the portable flow meter after the test. Only the transducer reading was recorded and stored. The time factor was added later, since the data recording frequency remains fixed at 50 Hz driven by the computer clock in the stationary flow meter and by a crystal in the portable flow meter.

Once the data have been stored, any suitable program with graphics capability can be used to retrieve and view the information. For example, small samples can be viewed in Microsoft Excel™. However, due to the sample rate of 50 Hz, most basic programs quickly run out of capacity if attempting to view large samples. Thus, SE EDL was also developed as a viewer, with several additional features such as breath count and volume calculations from the flow data.

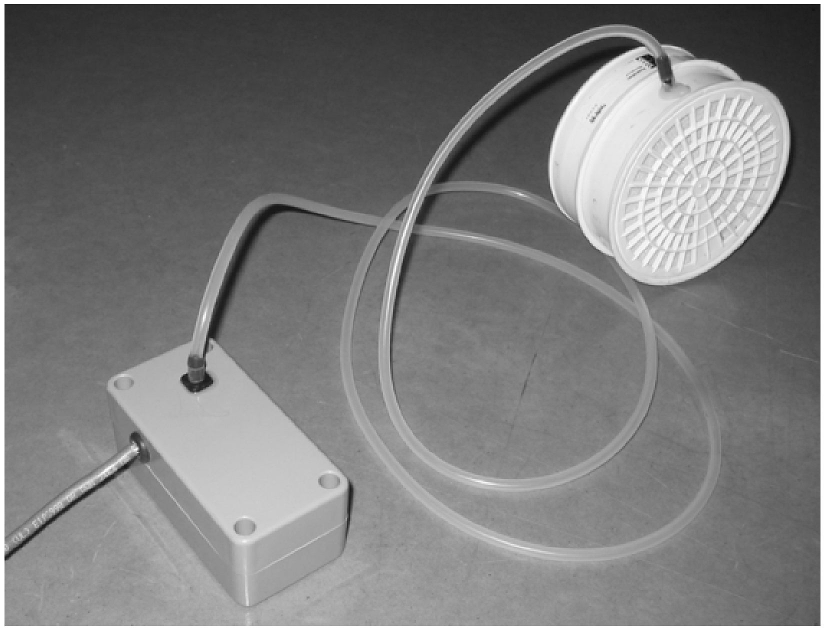

Figure 3. Flow meter assembly, comprising filter, flexible tube, and pressure transducer.

Calibration Procedures

A breathing machine/test bench of the Interspiro IPZ type (hereafter referred to as IPZ) was used. This test bench was used to calibrate the flow meter in a pulsating flow, *i.e.*, representing the inhalation-exhalation cycle of human breathing. The calibration was performed in the following manner. First, a personal computer was connected to the IPZ. Second, the lung of the breathing machine was then calibrated with a glass syringe (2.5 liters) in accordance with the calibration instructions. This procedure confirmed that the flow meter in the IPZ showed a correct value and that the artificial lung was of a known volume, 2.5 liters. Third, the motor was set at 25 rpm. This sinusoidal curve produced minute volume of 62.5 liters. As the IPZ produces a sinusoidal curve, the peak flow rate can be determined to be 196.25 L/min (volume multiplied with 3.1416) (NIOSH Procedure No. CET-APRS-STP-CBRN-0351). Fourth, a Sundström SR200 full face mask with a P100 filter was fitted to the dummy head on the IPZ, and the flow meter attached to the full face mask. Fifth, the output was monitored using in house test software. To establish the accuracy of following the breathing pattern, the breathing machine was then run at a number of different speeds, producing different peak inhalation airflows (PIAF) measured in liters per minute. All tests were conducted in a controlled-atmosphere test laboratory in order to minimize transducer drift.

The curve in Figure 4 was then compared with the curve recorded on the flow meter (Figure 5). The flow meter only recorded the inhalation, *i.e.* the negative portion of the sine curve in Figure 4. The positive exhalation portion was ignored. Note that in Figure*5*, the inhalation half of the curve was turned around, and each inhalation curve pointed upwards. By studying this graph we can clearly see that this system dose not introduce any lag, as the curves are identical.

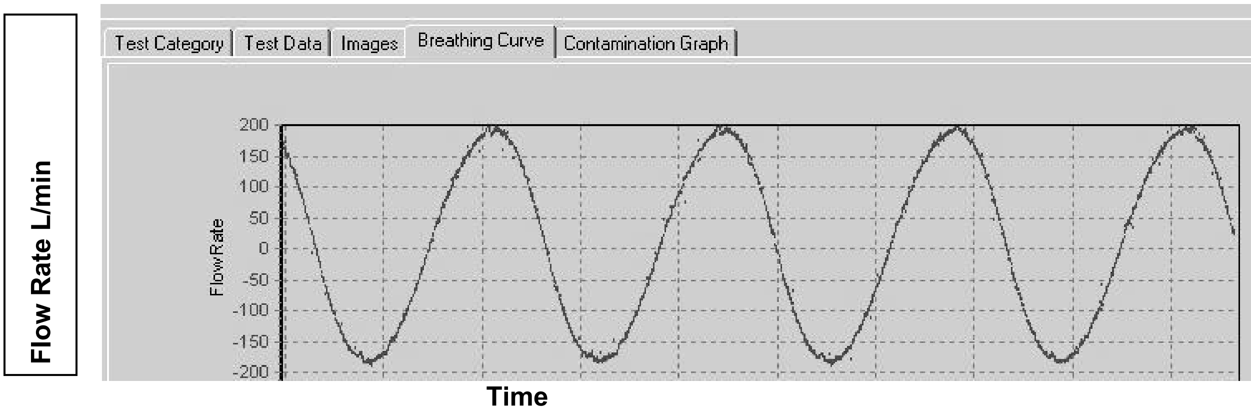

Figure 4. The flow rate from the IPZ breathing machine is shown as sine curve over time.

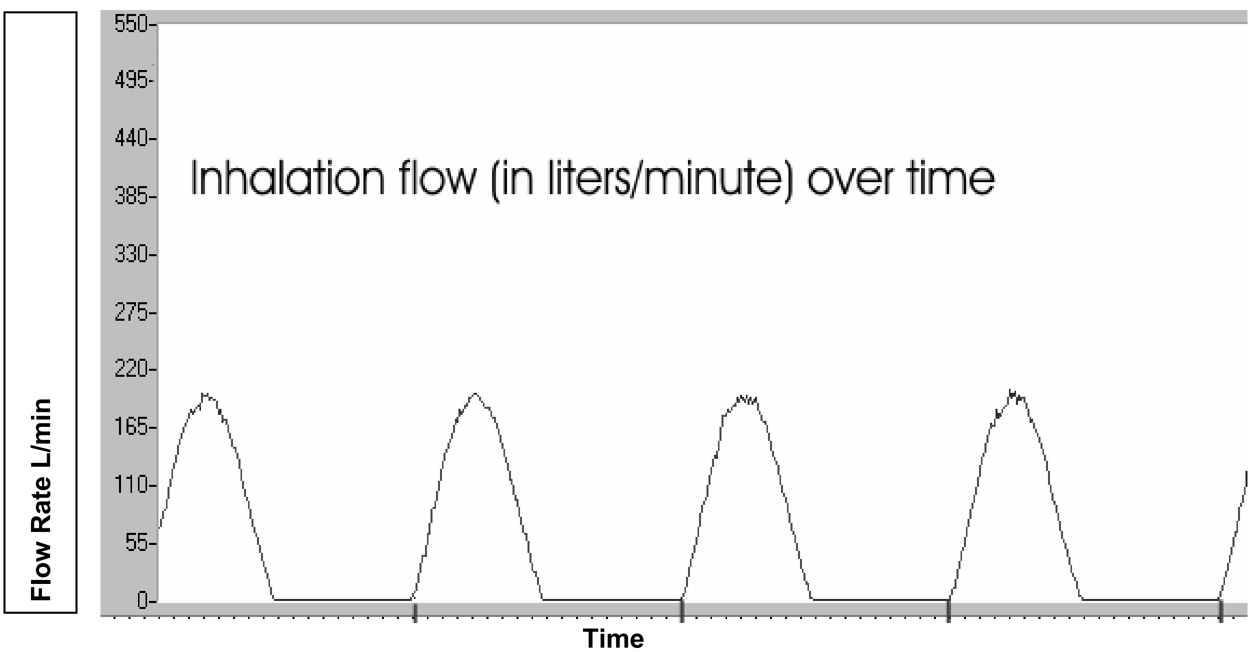

Figure 5. Inhalation flow from the flow meter is shown in real-time on the computer (same data as Figure 4).

Conditions In The Test Room

- Temperature: 23 ±3 degrees Celsius
- Humidity: 47% ±5%.

All data were recalculated back to standard temperature pressure dry (STPD) for easy comparison with other data.

Conversion of Flow Meter Readings to True Flow Values

This procedure has established the relationship between the collected data and the reference data, and demonstrated accuracy of the readings for a given flow. In order to establish reference data, the mask was fed with a dynamic flow at various breathing rates from the IPZ breathing machine. Based on preliminary testing and literature research (Nunn, 1993; Åstrand and Rodahl, 1986) airflow rates ranging from 100 to 550 liters per minute were used to establish the relationship between flow rates of the IPZ and the flow meter. Those different airflow rates were correlated to the airflow rate reported by the flow meter. To obtain true airflow rates, the readings from the flow meter were corrected using a regression equation derived from the relationship.

RESULTS AND DISCUSSION

A typical flow rate curve from the EDL viewer system is shown in Figure 6. A closer look at the breathing cycle is shown in Figure 7.

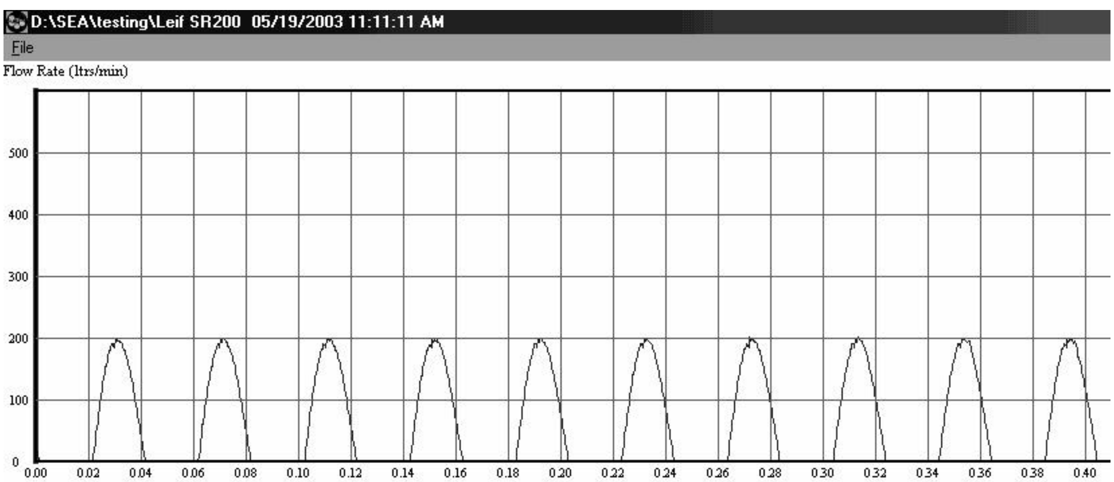

Figure 6. Flow rate (L/min) over time (The timeline is divided into 100ths of a minute. The graph shows 0.40 of a minute, or 24 seconds).

In the EDL software, the minutes are divided into 100 parts. Furthermore, the EDL software has several advanced functions, such as graphic display of peak flows. A closer look at the EDL graph (Figure 7) reveals that that in this sample the first inhalation lasts from approximately 0.02 to 0.04 minutes, a total time of 0.02 minutes or 1.2 seconds. The flow meter captured data at 50 times per second, ensuring a very accurate plot of each breath.

This sensitivity and accuracy is clearly demonstrated in Figure 7, where it is evident that the breathing machine had a small defect or inherent characteristic, creating a tooth in the curve near its peak. The output from the IPZ (Figure 6) is not so clear by comparison, merely showing the defect as fuzz on the curve.

During the period of collecting the data (Aug 2002 to March 2003) the flow meter was checked against the IPZ test bench 10 times. Repeated checkups were performed on the flow meter in the range 150–490 liters per minute as this was the most common range of data. Figure 8 shows the relationship between the IPZ and flow meter readings during calibration and the stability of flow meter readings over the period August 2002 to June 2003.

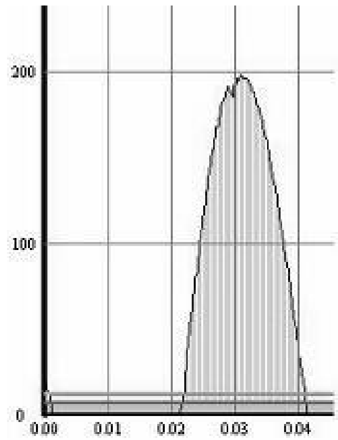

Figure 7. A single inhalation (a magnification of the first breath in Figure 6.) in liters per minute over time in minutes.

Conversion of Flow Meter Readings to True Flow Values

To obtain true air flow rates, the readings from the flow meter were corrected using a regression equation derived from the calibration data, *i.e.*, the relationship between the collected data and the reference data. The correlation coefficient for this regression was 0.9994. The true air flow rate (TAFR) was calculated as:

$$TAFR = - 0.000000000000004533910\ x^6 + 0.000000000008925053040\ x^5 - 0.00000006598949998243\ x^4 + 0.00002325942857606120\ x^3 - 0.00440380959190634000\ x^2 + 1.29929260688732000000\ x + 0.97778612410184000000$$

This method applied to all in-house tests, providing the opportunity to correct the data at a later time should the need arise. The “linearity” of the curve was always checked at the same time as each calibration check in order to enable future corrections.

Figure 9 shows the estimated errors between the corrected flow meter results and the true air flow rates. As can be seen from the data points, although errors are in the 4-5% range at flow rates of 100 liters per minute or less, the errors were within ± 3% over the range of 150–700 liters per minute. Therefore, the measurement error decreased with increasing air flow rates. Limited data points were collected for flow rates greater than 490 liters per minute.

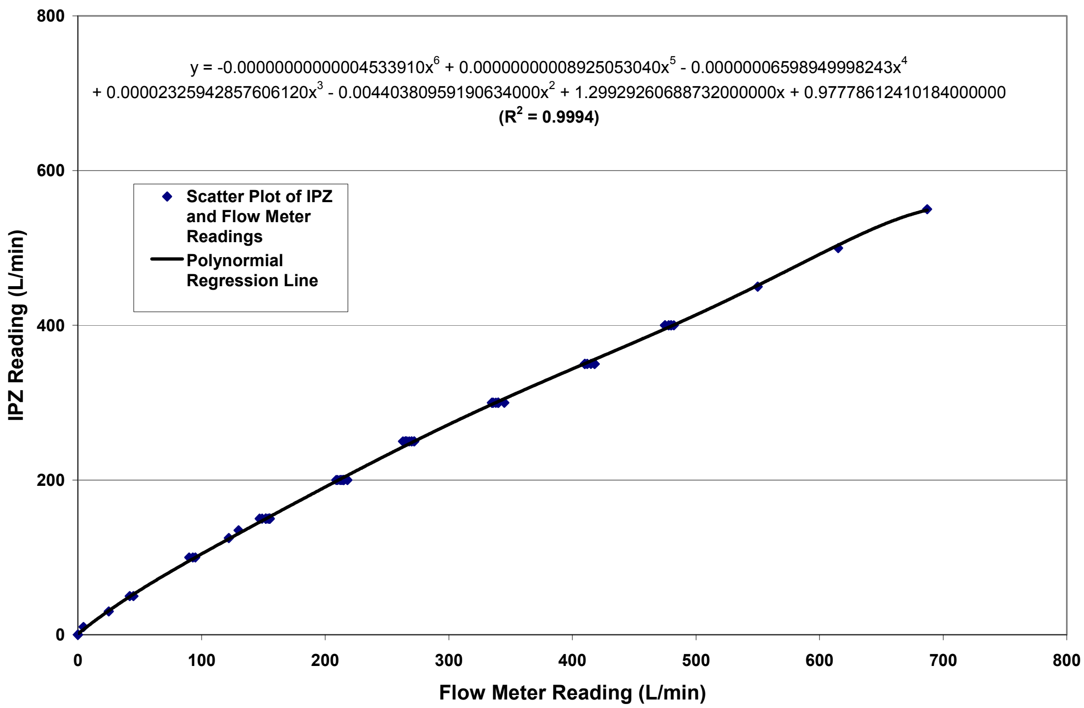

Figure 8. Plot of IPZ readings and data correction curve against flow meter readings.

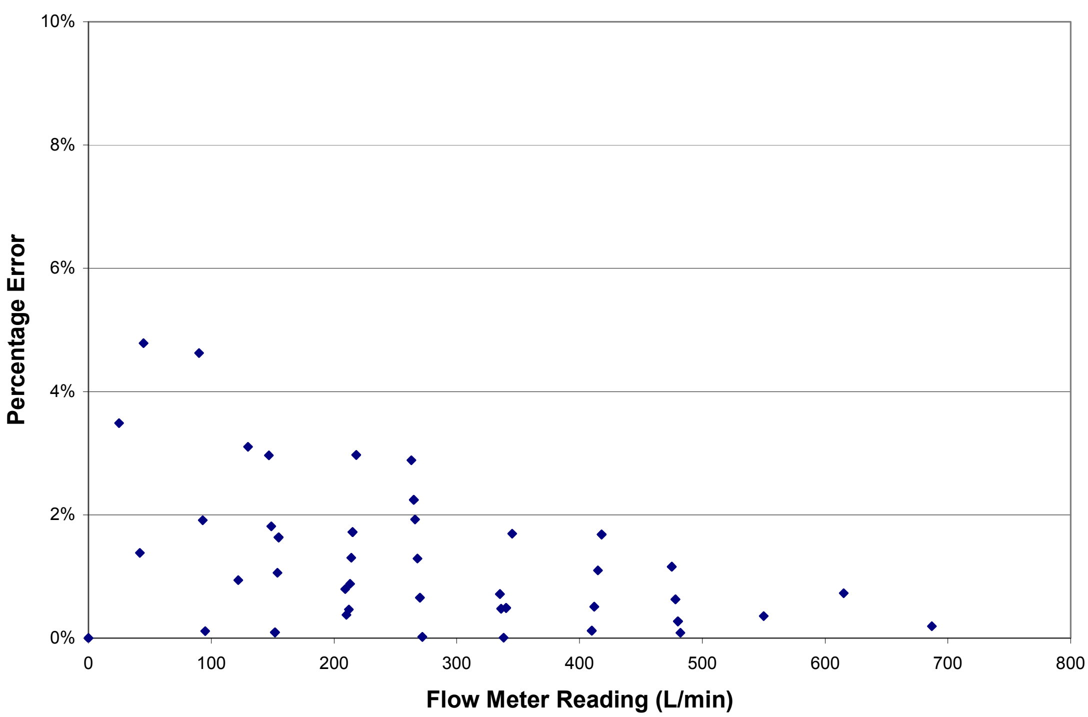

Figure 9. Flow meter errors as a function of flow meter reading.

CONCLUSIONS

The new simplified method of using a low resistance and measuring the pressure drop over the resistance did not have a problem with lag, and was very detailed, as the recording was done 50 times per second. The results clearly showed that the respiratory flow dynamics could be monitored and recorded with high accuracy and good resolution. This new simplified method and the data produced were deemed highly accurate for the full range of work rates that are potentially observed with the use of respiratory protection. The error rates were less than 3% over the full range of work rates (150–490 liters per minute). With accurate calibration and software correction, the measured values can easily be converted to give values that are very similar to those found with a breathing machine. More work is now needed to derive respiratory flow values during various kinds of operations in practical life.

Glossary

Breathing volume: the volume of air for a single breath, illustrated by the area shaded within the border of the inhalation flow curve (Figure 7) — (measured in liters per minute).

EDL: Extended Data Logging software. This software can be used to examine the airflows of every breath taken during long periods of time.

Inhalation flow curve: the curve representing the changes in flow rates during the inhalation phase of a breathing cycle.

Minute volume: The aggregate volume of all breaths drawn during one minute.

PIAF: Peak Inhalation Airflow. The highest flow generated during the inhalation phase of a breath.

STPD: Standard Temperature Pressure Dry. A benchmark applied to environmental conditions for easy comparison between tests made on different occasions.

Acknowledgements

The authors thank Sarah Clifford, Torbjörn Lundmark, and our families for their work and patience during the process of collecting data, conducting the tests and writing this paper. We also thank Robin Howie for his assistance in data analysis and last but not least Ziqing Zhuang for his advice and guidance in the preparation of this paper.

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