

Flow Measurement with Respironics Flow Sensors



ABSTRACT

Flow measurement issues with mechanically ventilated patients are reviewed with particular emphasis on the Respironics flow sensors. Flow sensor technology in the critical care setting is reviewed.

INTRODUCTION

The measurement of flow on mechanically ventilated patients requires attention to:

- sensor locations
- gas composition
- gas temperature
- inlet conditions
- humidity
- deadspace
- effective resistance of breathing circuit
- operating range of flow sensor

When comparing flow measured by two different devices all of these considerations must be taken into account. In addition, the degree of inter-unit and inter-sensor variability must be included in any evaluation.

FLOW SENSOR – OVERVIEW

Introduction – Airway Flow Measurement Techniques

Various technologies have been used to measure airway flow (Sullivan). Many of these techniques were developed strictly for precise short term laboratory measurements. These applications require meticulous attention to detail including calibration and operator attendance at all times.

For the relatively dry gas, laboratory quality airflow measurements, great attention is placed upon accuracy, calibration, repeatability, and precision. Flowmeters that perform suitably in these environments include Fleisch and Lilly style pneumotachometers, hot wire anemometers, rotating vane spirometers and ultrasonic vortex shedding flowmeters. Hot wire anemometers (also known as thermal dissipation devices), based upon the convective cooling by the flowing gas, often use heated (>300°C) plati-

num or a platinum alloy. As such these devices are inappropriate when flammable gases are present (Yoshiya). Rotating vane spirometers tend to underestimate at low flows and overestimate at high flows due to friction and inertia of the turbine (Hsley, Yeh). Overall, in respiratory research the most widely used flow measurement device is the Fleisch type differential pressure with a heated screen orifice.

A continuous, bi-directional airway flow measurement device that can be placed proximal to the patient and used in critical care environments has been of great interest. The continuous monitoring environment demands simplicity, reliability, ease of use and ability to continue working in wet, often mucous filled circuits for long periods of time without operator intervention. These devices should be relatively inexpensive, have minimal deadspace, work over wide flow ranges and require minimal or no calibration. Devices typically designed for the pulmonary function environment will generally not work well in continuous monitoring applications.

Due to the requirements in the critical care environment, a different type of flow device is required. These devices fall under the general description of fixed or variable orifice (aperture) differential pressure pneumotachometers. These flow measurement devices are usually simpler in construction, are typically lightweight plastic and thus can be disposable and designed to operate in wet, mucus filled patient airway circuits. Flow devices that offer the most promise in continuous proximal, bi-directional monitoring are those that utilize differential pressure pneumotachography.

Differential Pressure Flow Sensors – Theory of Operation

Differential pressure flow sensors incorporate some type of restriction (point orifice, variable flap, vena constriction, annular obstruction, target or linear flow restrictor) that generates a pressure difference across the sensor. Flexible tubing, attached to either side of the flow obstruction, transmits the differential pressure signal to a sensitive pressure sensor located inside a monitor at the bedside. Factors that influence the measurement of flow for this type of sensor include the gas molecular weight, temperature and airway pressure.

Fleisch Type

The popular Fleisch pneumotach uses small capillary tubes to ensure laminar flow through the sensor body thereby producing a nearly linear relationship between flow and differential pressure (Johns). While it is an excellent device for short term monitoring, it is easily contaminated by sputum and water condensate. Also due to its relatively large surface area (dead space) it is often not suited for continuous respiratory monitoring. In addition, it is heavy, costly and difficult to clean.

Lilly Type

The Lilly type flowhead uses a metal mesh for the flow restrictor. Hans Rudolph Company manufactures a version of this flowmeter that utilizes three screens to create a linear flow/differential pressure relationship. The Lilly suffers from the same problems as the Fleisch in monitoring continuous proximal airway flows.

Variable Orifice Type

The variable orifice type flow sensors have become popular in the long-term critical care monitoring environment due to their improved immunity to artifactual flow signals caused by moisture and secretions in the breathing circuit (Osborn). These flow sensors use a flexible sheet material (plastic or stainless steel) to create an opening that is small when flow is low and wider as flow increases. This dynamically changing orifice results in a more linear relationship between differential pressure and flow, allowing a larger range of flows to be measured accurately than is traditionally allowed by a fixed orifice type of device. The variable orifice flowmeter works quite well under conditions of moisture and mucous.

The variable orifice type flowmeter's accuracy depends, however, upon the consistent stress-strain characteristics of the variable orifice flap which can be degraded by inter-device variations created during manufacturing or intra-device changes due to fatigue during long-term use. In order to solve this problem, some manufacturers offer sensors with device specific factory pre-calibration parameters stored within a memory chip attached within the flowmeter connector. Variable flap flowmeters can be very susceptible to changes in flow patterns generated by different breathing circuit adapters (inlet configurations) placed immediately prior to the flowmeter.

Fixed Orifice type

The pressure drop across a fixed orifice flow sensor is, in general, proportional to the square of the flow (see Figure 1). Microprocessors can be programmed to store the parameters of these flow sensors and to compensate for this non-linear pressure-flow relationship. In addition, recent advances in differential pressure sensor technology have made it possible to measure

the very low flows reliably. The Respironics Flow Sensors are considered to be fixed orifice, target flowmeters. Although the Datex D-Lite[®] sensor (Merlainen) and MedGraphics preVent[™] Pneumotach (Porszasz) are also fixed orifice designs, as Pitot tubes they measure the velocity of gas flow and as such are based upon different measurement principles than target flowmeters such as the Respironics sensors.

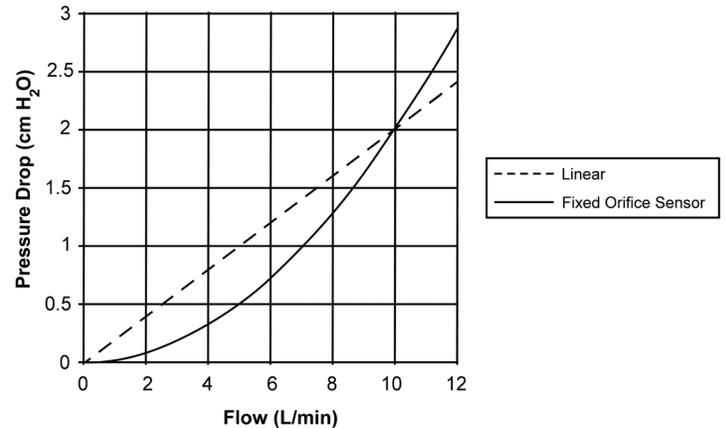


Figure 1 - Flow versus Pressure Drop for a “Linear” device (i.e. Fleisch pneumotachograph) and “Non-Linear” device (fixed orifice flow sensor)

Respironics Flow Sensor(s)

The adult flow and combined CO₂/flow sensors feature a target geometry composed of a center strut and side-mounted flow restrictions (having a notch in the strut) that are designed to minimize localized streamline effects about the pressure sensor aperture. This improves its performance compared to variable orifice flowmeters with changes in upstream geometry (adapter configurations). The design allows for immunity to unpredictable flow velocity profiles, without the need to add excessive length to the flow sensor adapter (minimal dead space). On the other hand, the neonatal flow sensors feature a target geometry composed of a center strut without the side-mounted flow restrictions to maintain an acceptable level of flow resistance. In order to reduce mechanical dead space, the combination pediatric/adult and neonatal CO₂/flow sensors are single piece designs.

As they have no moving parts, these flow sensors are simpler to construct and do not require user pre-calibration. Each configuration is characterized once at the factory, and with manufacturing control, individual sensor calibration is not required.

As previously noted, with a fixed orifice device, the differential pressure varies as the square of the flow. The measured flow should be corrected by use of empirically determined coefficients due to variations from this relationship and the assumptions made in developing the flow equations.

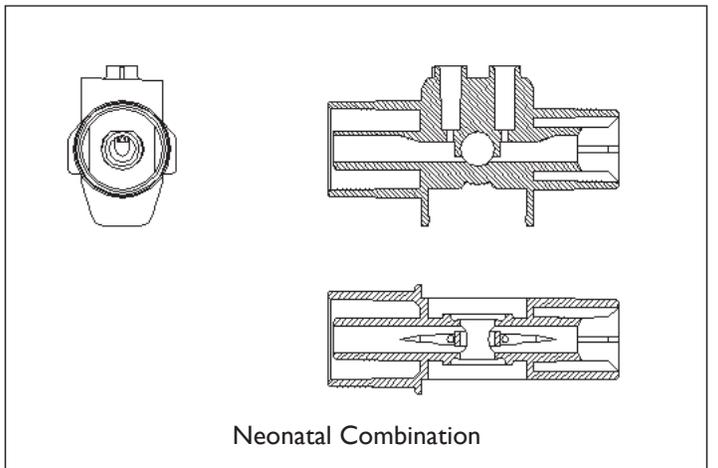
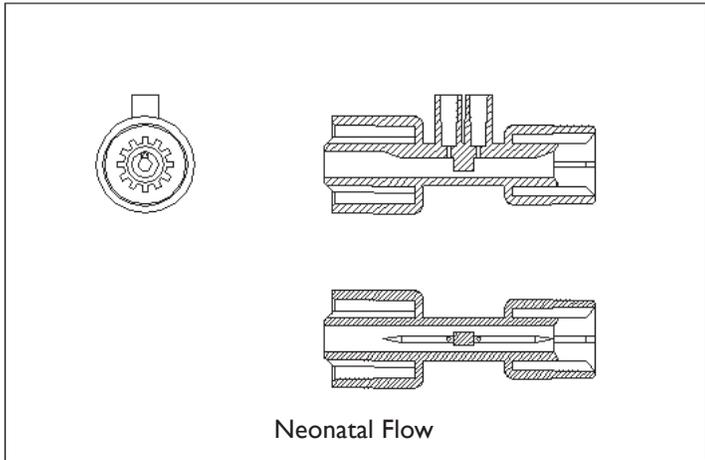
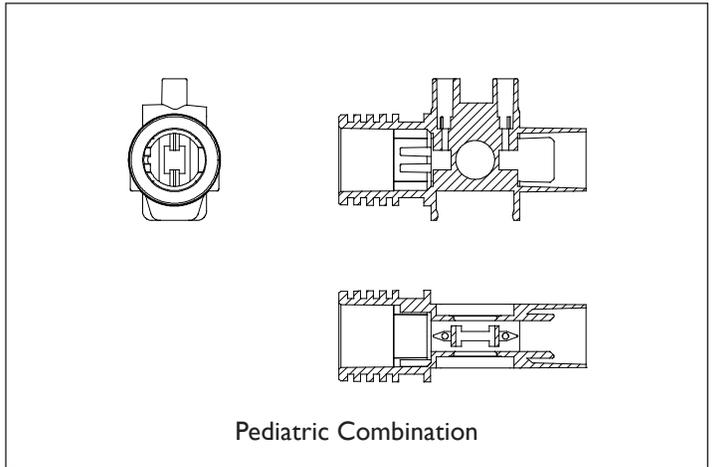
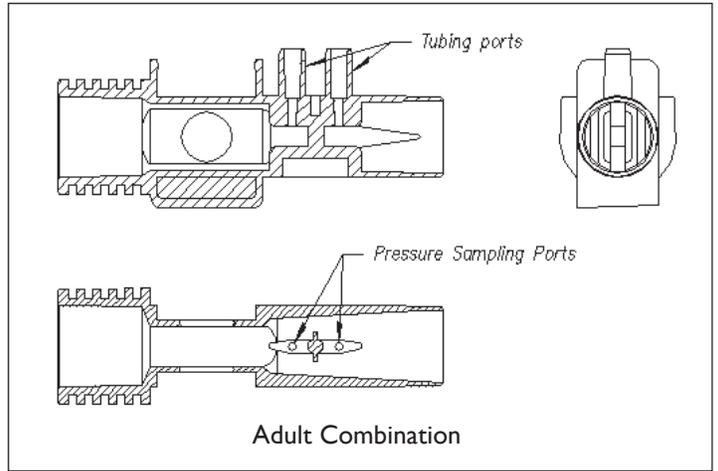
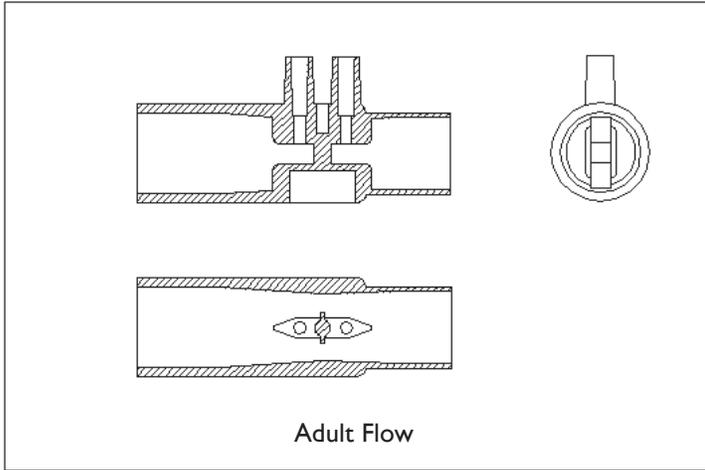


Figure 2 - Adult, neonatal, combination adult, combination pediatric, and combination neonatal CO₂/flow sensors – side, top and end sections

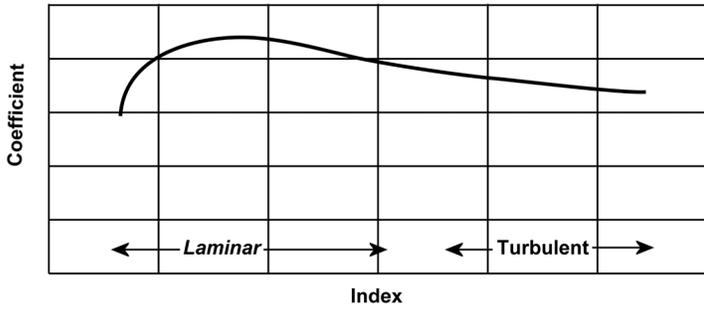


Figure 3 - Representative Correction Coefficient Curve

The relationship between the measured differential pressure to flow (L/min) can be described by the equation,

$$\frac{P_m T_{std}}{P_{std} T_m} K \sqrt{\Delta P}$$

where P_m , P_{std} , T_m and T_{std} are the measured and standard pressures (in mmHg) and temperatures (in °K), respectively; K is a correction factor that includes gas composition and other factors and ΔP is the differential pressure (in mmHg).

The $P_m T_{std} / P_{std} T_m$ is the ideal gas law correction of calculated flow to standard conditions. Inspiratory and expiratory phases are treated separately with regards to temperature and gas composition. For example in an unheated breathing circuit supplied with 'room' air, inspiratory air may be considered to be at near room temperature and consisting of nominally 21% oxygen and balance nitrogen and expiratory air at body temperature (or near body temperature less 2-4°C for temperature drop from 'lungs' to sensor) and consisting of nominally 16% oxygen, 5% carbon dioxide and balance nitrogen. While in a heated circuit with elevated oxygen (such as 60% FiO_2), the values used for both temperature and gas composition would be quite different.

FACTORS AFFECTING FLOW READINGS

Sensor Location

Proximal flow measured at the patient's airway can be substantially different from flow measured inside or at the ventilator. Many ventilators measure flow, not at the proximal airway, but close to the ventilator (see Table 1). This can result in a substantial difference between what is delivered to the patient and what the ventilator reports as delivered due to the wasted compression volume. This wasted portion of the tidal volume does not ventilate the patient, remains within the breathing circuit and tends to elongate and distend the breathing circuit tubing and compress the gas. A correction for this effect which is

proportional to the inspiratory peak pressure is applied by some ventilators given that the breathing circuit compliance is known. Even with this correction applied, precise estimation of the compression volume is difficult due to variations between individual breathing circuits, use of humidifiers, HMEs and other circuit components. Thus, for monitoring patients the sensor should be placed between the breathing circuit wye and the endotracheal tube.

Table 1 - Flow Sensor Location

Ventilator/Monitor	Flow Sensor	Site
Philips-Respironics NM3	Fixed orifice	Proximal airway
Puritan-Bennett 840	Hot wire	Distal to exhalation valve
Puritan-Bennett 840 (neonatal option)	Fixed orifice	Proximal airway
Philips-Respironics V200	Hot wire	Distal to exhalation valve
Hamilton Medical Galileo	Variable orifice	Proximal airway

Gas Composition

Accurate flow measurement requires that the nominal values for inspiratory and expiratory gas composition be provided. The user can choose typical ambient values for oxygen, carbon dioxide, and nitrogen if one is testing with a calibration syringe or typical patient values. Compensations for additional gases such as nitrous oxide, helium, or an anesthetic agent are available. The effect of not properly compensating for the gas concentrations may result in a significant change in the reported flow value (see Table 2). Gas composition correction assumes the viscosity can be computed as the linear combination of the product of each individual viscosity and its gas fraction.

Table 2 - Changes in Reported Flow and Percentage Difference with Different Gas Compositions (at 35°C).

N ₂ %	O ₂ %	CO ₂ %	He %	N ₂ O %	Agent %	Flow L/min	% Diff
79	21	0	-	-	-	100.0	-
79	16	5	-	-	-	99.0	1
Elevated Oxygen							
70	30	-	-	-	-	99.4	1
60	40	-	-	-	-	98.7	1
40	60	-	-	-	-	97.4	3
20	80	-	-	-	-	96.1	4
0	100	-	-	-	-	94.9	5
Anesthesia							
0	60	0	-	40	0	87.6	12
0	55	5	-	40	0	86.8	13
0	40	0	-	60	0	84.0	16
59	40	0	-	0	1	96.1	4
35	60	0	-	0	5	86.4	14
25	60	0	-	0	15	72.1	28
Heliox							
-	40	-	60	-	-	143.5	44
-	30	-	70	-	-	159.2	59
-	20	-	80	-	-	180.5	81

Gas Temperature

Accurate flow measurement also requires that the nominal values for inspiratory and expiratory gas temperature values be considered. The software provides defaults for typical patient values. If the inspired air is heated in the breathing circuit, greater accuracy can be achieved by entering the set temperature of the heater as the inspiratory temperature.

Inlet Conditions

The adult and neonatal flow sensors have been designed to minimize sensitivity to changes in inlet conditions. For example, changing the proximal connections from a direct endotracheal tube (ET) connection to a connection via an elbow has a dramatic effect on the cross-sectional profile of the flow entering the flow sensor, but with a robust design this should have little effect on the flow measured (see Figure 4).

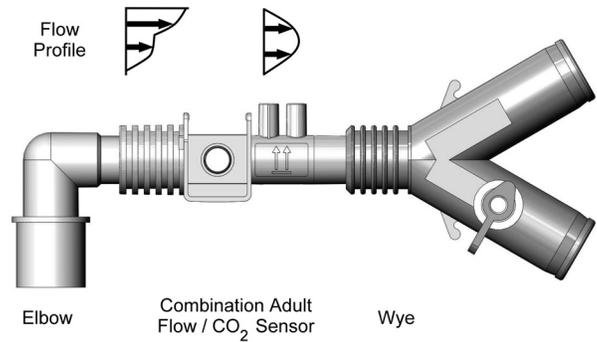


Figure 4 - Combination adult CO₂/flow sensor in-circuit with example expiratory flow velocity profiles.

Even small changes in the geometry of the breathing circuit tubing relative to the flow sensor can have a significant effect on the measured flow. The Respironics adult and neonatal flow sensor are only slightly affected (typically <5%) by such changes, whereas, other devices can be significantly affected. For example, it has been demonstrated that Fleisch pneumotachographs connected between the wye and endotracheal tubes exhibit a flow rate dependent error in measured flow up to 10% (Kreit).

To quantify this effect in the flow sensors, commonly used adapters were attached individually to the inlet of the flowmeter and the resulting changes in flow recorded. To test the flow sensors, flows of 20 and 60 L/min, and 5 and 20 L/min were used for the adult and neonatal flow sensors, respectively. Various elbows, endotracheal tubes CO₂ airway adapters, Heat Moisture Exchanger (HME) and straight 22 to 15 mm adapters were used to test expiratory flows, and different wyes were used to test inspiratory flows.

If sufficient entrance length is provided in the flow sensor, then laminar flow and a consistent flow velocity profile can be achieved. However, this is usually not practical so entrance length to a flow sensor must be traded off against the design requirement of minimal dead space. Thus, a balance has been sought between low dead space and insensitivity to changes in inlet conditions. The design of the flow sensors has sought to optimize this balance.

Humidity

The flow sensors have been designed to be insensitive to moisture accumulation on the flow sensor. The measurement and generation of the pressure drop can be affected by moisture. The user's manual and product package labeling indicate the pressure ports should be directed upwards to prevent fluid from draining into them. The shape and placement of the target are such as to minimize accumulations on the sensor. However, proper breathing circuit maintenance and avoiding gravity dependent positions within the breathing

circuit is still required to avoid pooling of water and sputum in the flow sensor. Bench and clinical testing in fully saturated breathing circuits have demonstrated that the effect of moisture is typically negligible in the adult sensors and small in the neonatal sensors.

When the flow sensors are used in a heated breathing circuit, the temperature for the nominal expired gas temperature (e.g. 35°C) should be entered and the reported volumes will be approximately Body Temperature Pressure Saturated (BTPS). If the flow sensors are used for testing in a dry room temperature circuit, the room temperature should be entered and the reported volumes will be in Ambient Temperature Pressure (ATPx). (For a more detailed discussion of these issues - refer to Proximal Flow Measurement with the Flow Sensors whitepaper).

Dead Space – Equipment

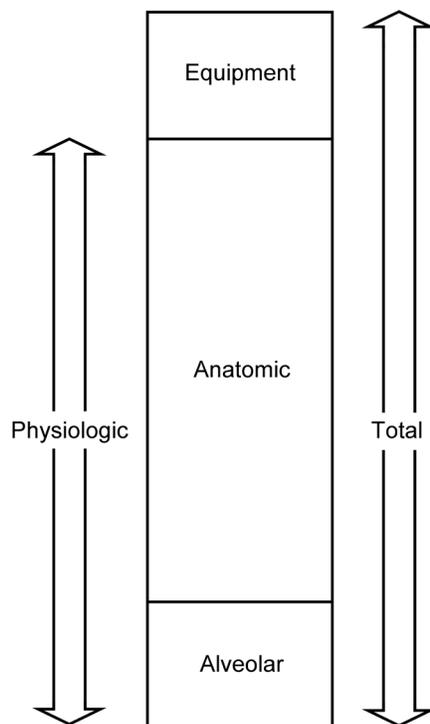


Figure 5 - Breakdown of Different Deadspace Volumes

The equipment (i.e. apparatus) dead space in the ventilator circuit (See Figure 5) can be substantial relative to the total tidal volume, especially when large HME filters are used. One of the design goals for each of the flow sensors was to keep the added dead space to a minimum (<10 ml for the adult flow sensors and < 1 ml for the neonatal sensors).

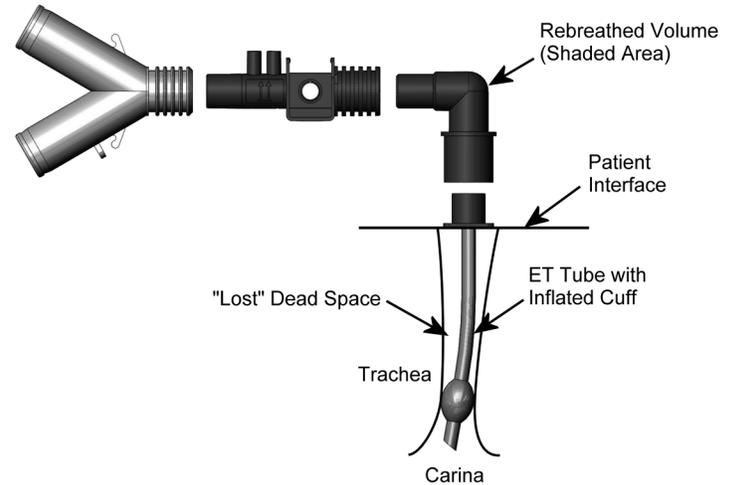


Figure 6 - Anatomic and apparatus deadspace in intubated patient

Effective Resistance of Breathing Circuit

The addition of a flow sensor to a breathing circuit should have minimal impact on the measured quantity - flow. One of the design goals was to minimize the resistance as measured by the pressure loss across the sensor while maintaining as large as possible recoverable differential pressure drop between the ports. Typically, resistance of a flow meter in product specifications and standards for pulmonary function testing is stated in terms of a pressure drop or resistance at a particular flow rate. For a fixed orifice flowmeter, due to the parabolic nature of resistance the device is typically much less resistive at low and moderate flows than devices that have a linear flow pressure relationship. Conversely at higher flows it is more resistive than the linear flow devices. For example, let's consider the two devices with identical pressure drop at 10 L/min and the flow-pressure characteristics as in Figure 1. With a typical inspiratory square waveform or sinusoidal waveform with PIFs of 6 and 10 L/min, respectively, the added work for the neonatal sensor would be less in both conditions. When reading resistance specifications it is important to consider both the flow rate at which the pressure drop is reported and the nature of the flow-pressure relationship. In addition, for devices that do not have a linear relationship a more relevant measure would be a flow-pressure plot or a better figure of merit that reports the added work of breathing due to the device under specified conditions rather than the pressure drop at a particular flow rate.

Operating Range of Flow Sensor

While the operating range for flow is constrained by the range of the pressure sensors and electronics, the operating range of derived parameters such as volume must be considered in light of the flow sensor range and physiological limits. For example,

the specification for the adult tidal volume range is from 100 ml to 3000 ml. However, the system cannot measure these volumes to the stated accuracy at all possible I:E ratio and frequency settings because of the high limit of 180 L/min or low limit of 2 L/min. Consider the frequency range from 2 to 120 breaths per minute and the volume range with a typical I:E ratio. The drawing of a rectangle below with the range limits might imply that all combinations within that area are possible. However, flow and physiological limitations must be considered and instead the shaded area (see Figure 7) is the region which can be measured given the 1:2 I:E ratio and flow range of 2 to 180 L/min. As a reference point, competitive flowmeters do not have such a wide operating range.

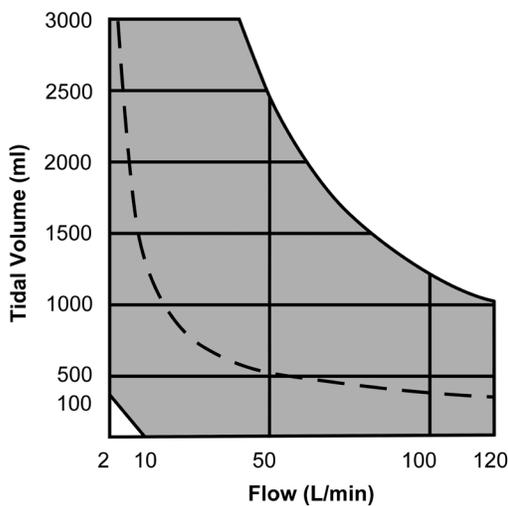


Figure 7- Example Operating Range of Adult Flow Sensor (Upper range of neonatal flow sensor shown as dashed line)

Inter-Sensor Variability

The flow sensors use a fixed orifice type design which allows for a single piece injection molded part. This means that there should be no need for individual device calibration of the flow/pressure characteristics. To compare the variability between 20 adult flow sensors, volume tests were performed at a nominal flow rate of 60 L/min. Similarly, to compare the variability between 20 neonatal flow sensors, volume tests were performed at nominal flow rates of 10 and 20 L/min. The same module was used to remove the effect of inter-unit differences. The average inspiratory and expiratory percent error of the 20 different devices tested for each flow was computed. The error, the standard deviation of the average volumes for the 20 devices, a measure of the sensor to sensor variability, was also computed. The standard deviations for

all of the sensors (< 1%) are well within the ability to accurately repeat the volume test, which shows that interchangeability is excellent and that individual characterization (thus calibration) of each flow adapter is not required.

Inter-Unit Variability

Due to tolerances in the manufacturing process there is a small amount of variability in the data acquisition electronics from unit to unit. To determine the variation at different flow rates between different units, 4 modules were tested with the same neonatal flow sensor and inter-device differences computed. Inter-unit differences were determined to be less than 1% overall which is considered excellent inter-unit variability. The coefficient of variation was typically less than 0.5% except at the lowest flow settings, which are the most difficult to measure with high accuracy and repeatability.

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