Proximal Flow Measurement with Respironics Flow Sensors

RESPIRONICS
Envisioning tomorrow. Improving today.

ABSTRACT

Measurement issues of proximal flow in mechanically ventilated patients are reviewed relative to traditional flow measurement at the ventilator.

INTRODUCTION

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. 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 and differences due to humidification. This wasted portion of the tidal volume, i.e. compression volume, does not ventilate the patient, remains within the breathing circuit and tends to elongate and distend the breathing circuit tubing. A correction for this effect which is proportional to the inspiratory peak pressure is applied by some ventilator manufacturers 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. In a typical breathing circuit, the gas conditions such as temperature may vary from room air to body temperature and humidity may vary from dry air to fully saturated air (Figure 1). Thus, for more accurate monitoring of delivered volumes and of the patient's expired volume, the flow sensor should be placed between the breathing circuit wye and the endotracheal tube.

The combined CO_2/Flow sensors from Respironics allow both proximal mainstream capnography and spirometry to be performed using a single compact sensor. For a thorough description of issues associated with flow measurement with Respironics flow sensors see Respironics' white paper entitled "Flow Measurement with Respironics Flow Sensors" and for a discussion of the selection criteria for these sensors see Respironics white paper entitled "Selecting the Right Respironics Combined CO_2/Flow Sensor".

Gas Conditions

Gas volumes may be expressed at different conditions and differences between these conditions have often led to confusion. Conventionally, ventilation is reported at BTPS (body temperature of 37°C, ambient pressure, and saturated with water vapor) while gas volumes associated with carbon dioxide elimination (VCO_2) and oxygen consumption (VO_2) are reported in STPD (standard temperature 0°C, pressure 760 mmHg and dry). To convert between the different conditions, the ideal gas law, $PV = nRT$ (where P is pressure in absolute terms, V is volume, n moles of non-water molecules, R is 62.3656 liters mmHg per mole degree and T is temperature in absolute terms) is applied at the two different gas conditions.
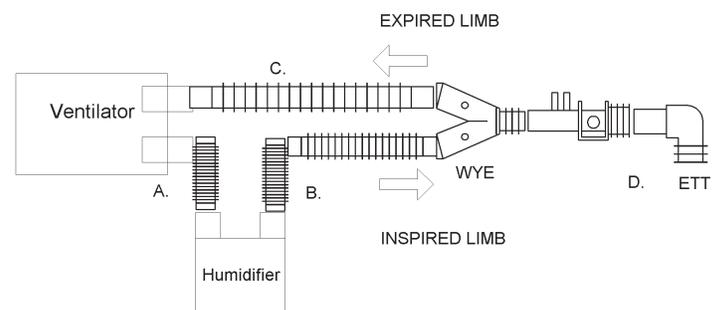

Figure 1 - Ventilator with breathing circuit with humidifier on inspiratory limb. Conditions at A through D are described below:

A Gas from the ventilator inspiratory port consists of room air or an elevated level of oxygen. The gas is typically dry and at room temperature which is nominally 25°C.

B Gas exiting the humidifier is typically at 100% relative humidity (RH) (i.e. saturated) and at a temperature greater than room temperature and less than or equal to body temperature of 37°C.

C Gas returning from the patient is less than 100% RH due to condensation and at a lower temperature (such as 33°C).

D Gas expired at the patient's mouth is most likely slightly less than body temperature of nominally 37°C and fully saturated. Gas inspired at the patient's mouth is less than 35°C due to cooling from the humidifier through as much as 8 feet of 15 mm ID breathing circuit tubing.

Dalton demonstrated that the pressure of a gas is independent of the number of other gases present. Thus, the partial pressure of a gas in a gas mixture is the pressure that this gas would exert if it occupied the total volume of the mixture in the absence of other components. For humidified air Dalton's law can be written as:

$$P_B = P_{O_2} + P_{N_2} + P_{CO_2} + P_T + P_{H_2O}$$

where P_B is the ambient barometric pressure and P_{O_2}, P_{N_2}, P_{CO_2}, P_T and P_{H_2O} are the partial pressure of oxygen, nitrogen, carbon dioxide, trace gases and water vapor.

If this equation is written as the sum of the dry gases and water vapor then:

$$P_B = P_G + P_{H_2O}$$

where P_G is the partial pressure of the dry gases of oxygen, nitrogen, carbon dioxide and trace gases (argon etc).

The total pressure of the non-water molecules can be seen to be the total pressure less the water vapor pressure. Thus, to convert from condition 1 to condition 2 the following is obtained:

$$\frac{(P_1 - P_{1H_2O})(V_1)}{(273 + T_1)} = \frac{(P_2 - P_{2H_2O})(V_2)}{(273 + T_2)}$$

If condition 1 is BTPS and condition 2 is STPD then:

$$\frac{(P_B - 47)(V_{BTPS})}{(273 + 37)} = \frac{(760 - 0)(V_{STPD})}{(273 + 0)}$$

where 47 mmHg is the water vapor pressure at 37°C the body temperature and 0 and 760 mmHg are the standard temperature and pressure, respectively.

Simplifying this equation results in:

$$V_{STPD} = \frac{(P_B - 47)(V_{BTPS})(273)}{(760)(273 + 37)} = \frac{(P_B - 47)(V_{BTPS})}{(863)}$$

Using these expressions, one can calculate the volumes at different conditions. Assuming no compression loss, a volume of 450 ml measured at ATP (ambient temperature and pressure) conditions by a flow sensors at the inspiratory limb (Point A Figure 1) would be seen as 500 ml at BTPS conditions by a flow sensor proximally located (D) and 475 ml at the expiratory port (C) because of thermal expansion and the addition of water vapor at point A.

The flow calculation inside of the Respironics flow measurement systems converts measured flow and volume to the equivalent in ambient conditions. Because the conditions of the inspired gas are unknown (active or passive humidification, heating, etc.), inspired gas flow and volumes are converted to their equivalent at expired temperature. The equation for the flow calculation used in flow measurement systems includes the ratio T_E / T_f where T_E refers to the temperature, in K, of the standard or reference gas and T_f refers to the temperature of the flowing gas. T_E is the set expired gas temperature, although it is also used where the flow is inspiratory because during inspiratory flow, the ratio of temperatures converts the flow to its equivalent volume at expiratory temperature. During expiratory gas flow, the ratio of temperatures in the flow equation is always equal to 1.0.

A Note on BTPS conversion

For expiratory gas flow, there is no need to consider the temperature ratio portion of the flow calculation when converting to BTPS. The straightforward conversion is as earlier stated

$$V_{BTPS,E} = V_{M,E} \left\{ \frac{P_B - P_{H_2O}(RH_E, T_E)}{P_B - P_{H_2O}(100\%RH, 37°C)} \right\} \left\{ \frac{273 + 37}{273 + T_E} \right\}$$

where V_M is the volume measured at ATPx.

For inspired gas conversion it may be helpful to assume that since the ratio of temperatures is incorporated into the flow conversion, the T_I terms cancel giving the equivalent of a conversion to BTPS from the set inspired gas conditions.

$$V_{BTPS,I} = V_{M,I} \left\{ \frac{P_B - P_{H_2O}(RH_I, T_I)}{P_B - P_{H_2O}(100\%RH, 37°C)} \right\} \left\{ \frac{273 + 37}{273 + T_E} \right\}$$

Note that the true value for T_I is used in the P_{H_2O} calculation and is entered into the Respironics flow measurement system.

Also, note that when testing under non-clinical bench conditions, further compensation is needed to convert from the clinically reasonable T_I and T_E to the actual bench conditions.

Table 1 - Conditions at Different Points in Figure 1

Point	Temp ($^+$C)	PH$_2$0 (mmHg)	Volume (ml)	%RH
A	25	0	450	0
B	37	47	500	100
C	33	19.5	475	50
D	37	47	500	100

Note: The value chosen for temperature and humidity are only to illustrate that different parts of the circuit have different conditions and not to serve as an example for any specific configuration.

The effect of humidification on the measurement of volume is often a point of confusion and needs to be clarified. Within the airways the respiratory gases can be considered to be effectively saturated with water vapor. As such, the vapor pressure of water depends entirely on temperature. To calculate water vapor pressure for a saturated system, different equations have been developed including a very precise equation consisting of a logarithmic function (Golff and Gratch). Respironics systems employ a quadratic equation (Figure 2) that provides a reasonable degree of accuracy. Data from a table of water vapor pressure was plotted along with the quadratic curve. The maximum difference between this data and the plotted curve is less than 2 mmHg with an effect of approximately 0.2% on the calculated volume. Relative humidity, a measure of saturation for moist air, is calculated as the ratio of partial pressure of water (P_{H_2O}) over the vapor pressure of water (P_{vapor}) at the same temperature.

$$\%RH = 100 \cdot \frac{(P_{H_2O})}{(P_{vapor})}$$

Rearranging this equation, the partial pressure of water may be calculated as the product of the relative humidity and water vapor pressure. This discussion has not considered aspects of cooling, rain out and the associated temperature gradients and humidity changes that occur in breathing circuits. For more detail on humidification and mechanical ventilation please consult a recent review paper by RD Branson.
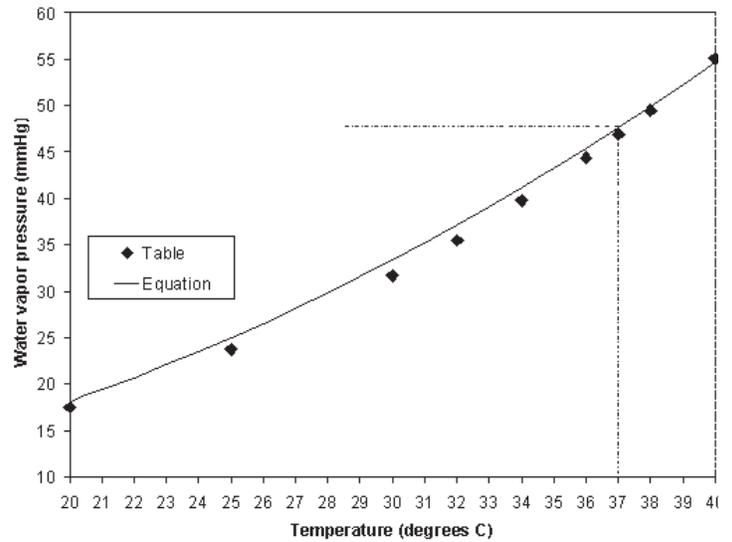

Figure 2 – Water Vapor Pressure as a function of temperature.

Table 2 – Different Types of Humidification

Humidifier	Restrictions	Clinical Applications
Cold-water Humidifiers	• Intact airway • O$_2$ therapy with abnormal or high fresh-gas flow	• O$_2$ therapy • CPAP
Hot-water Humidifiers	• Ventilatory support with abnormal airway, high Vmin large fresh-gas flow, large gas volume	• Oxygen tents • Head boxes • ICU • Anesthesia • Pediatrics • CPAP
Nebulizers	• High fresh-gas flow • Head boxe • Large volumes • Sputum clearance	• Oxygen tents • CPAP • HFV • Physiotherapy
Heat and Moisture Exchangers	• Ventilatory support with normal airway and normal minute ventilation	• Infection control • ICU • Anesthesia • Transport

Table adapted from MP Shelly, 1992.

The example in Figure 1 assumed a hot-water humidifier. However, to complicate matters further, humidification may be accomplished via different means resulting in different temperatures and humidities. Table 2 lists common means of humidification. The associated temperatures and resulting partial pressures of water for each must be considered for proper compensation.

Gas Compression

The ventilators "measured volume" is often displayed but can be significantly higher than the actual delivered volume due to compression loss in the breathing circuit in ventilator systems. While this is widely known it is not fully appreciated (MJ Tobin). The compression volume is related to the internal volume of the ventilator, volume of the humidifier (if present), volume and elasticity of circuit tubing and volume of other components of the breathing circuit such as HMEs etc. The volume due to compression loss that does not reach the patient becomes increasingly important as pressures increase and volume decreases. During the inspiratory portion of a ventilator-delivered breath, compression occurs throughout the breathing circuit and the breathing tubing distends and elongates. During the expiratory portion of a ventilator delivered breath, the compressed gas and stored energy in the distended and elongated breathing tubes is released and this additional volume is measured by sensors at the exhalation port of the ventilator. Unless volume measurements are made directly at the patient's airway the exhaled volume displayed by the ventilator may overestimate the patient's actual tidal volume by the compressible volume (Tobin). Some ventilators allow for a correction factor (i.e. compression factor) of the measured volume for circuit compression volume. The factor, calculated as compression volume over the corresponding ventilation pressure, allows a compressible volume to be estimated by multiplying this factor by the peak pressure less PEEP. Compression factors are specific to the breathing circuit and the components used (humidifier, HMEs etc) and are subject to error. Failure to account for the wasted compression volume could result in hypoventilation in ventilator supported patients. Studies of several ventilators found that the discrepancy between displayed and proximally measured volume was as high as 23% (Gammage) and varied significantly on the same ventilator with different brand breathing circuits (Bartel).

Other Effects

Depending on the specifics of the design of the sensor and technology, other effects include inlet conditions and gas density and/or viscosity effects. The Respironics sensors are only slightly affected by changes in inlet conditions, 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). Additionally, accurate flow measurement requires that the nominal values for the inspiratory and expiratory gas composition be provided. The Respironics flow sensors correct the inspiratory and expiratory flows using nominal gas concentrations. This correction is relatively insensitive to differences seen between inspiration and expiration. In fact, inspiratory expiratory gas differences due to the replacement of oxygen with carbon dioxide results in only a 1% effect on the measured flow (Table 2 – Respironics white paper entitled "Flow Measurement with Respironics Flow Sensors").

CONCLUSION

When using volume measurements in breathing circuits consideration must be given to the effects of gas conditions, compression volumes and location of the flow sensors so that the values may be properly interpreted. If possible, proximal flow sensors should be used to minimize the problems associated with gas conditions and compression.

REFERENCES

(1) Bartel, LP, Bazik, JR and DJ Powner. Compression volume during mechanical ventilation: Comparison of ventilators and tubing circuits. Crit Care Med, 1985; 13(10): 851-854.

(2) Branson, RD. Humidification for patients with artificial airways. Resp Care, 1999; 44(6): 630-641.

(3) Gammage, GW, Baner MJ, Blanch PB, Kirby RR. Ventilator displayed tidal volume: What you see may not be what you get (abstract). Crit Care Med 1988; 16:454.

(4) Golff, JA and S Gratch. Low-pressure properties of water from −160 to 212 deg F, Trans Am Soc Heat Vent, 1946; 52: 95-122.

(5) Kreit, JW, and FC Sciurba. The accuracy of pneumotachograph measurements during mechanical ventilation. Am J Respir Crit Care Med, 1996; 154: 913-917.

(6) Prusaczyk, WK. Precise water vapor pressure value calculations. Comput Biol Med, 1989; 19(2), 129-130.

(7) Shelly, MP. Inspired gas conditioning. Resp Care, 1992; 37(9): 1070-1080.

(8) Tobin, MJ. Principles and practice of mechanical ventilation. McGraw-Hill, Inc. New York, 1994.