WHITE PAPER

Volumetric Gas Measurements – Measurement Site Considerations

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ABSTRACT

For the measurement of gas exchange (such as carbon dioxide elimination), the choice of the gas and flow measurement sites can significantly influence the accuracy of the resulting measurement. The pros and cons of these different measurement sites are discussed.

INTRODUCTION

The computation of a volume of a gas component as is performed for carbon dioxide elimination or oxygen consumption requires the proper combination of the flow and gas measurements. This combination, (i.e. signal integration) requires precise timing and frequency matching of the flow and gas concentration signals. Historically, mixing chambers have been used to physically average the expired gas signal thereby eliminating the need for signal timing precision. Although mixing chambers are effective for measurement of mixed expired gas values, they are also bulky and do not permit end-tidal gas concentration measurement and single breath volumetric analysis. With today's compact systems, measurements of flow and gas partial pressure (or concentration) are undertaken using flow and gas sensors that may or may not be located proximally and in the mainstream flow. In the case of a ventilator, the delivered flow in the inspiratory limb of the breathing circuit and the exhaled flow from the expiratory limb are typically measured internally by two separate flow sensors. Gas concentration may be measured at or near the patient airway, (known as mainstream measurement), measured distally from the patient's airway, or a portion sampled and measured by a system located a distance from the sample site (known as sidestream measurement). A challenge is to combine the concentration and flow signals in such a way that the temporal relationship between these two variables is accurate. This paper will discuss tradeoffs and potential errors incurred with the use of different measurement sites for flow and CO_2 and sampling methods of CO_2.

CO_2 ELIMINATION

CO_2 elimination "$\dot{V}CO_2$", often incorrectly referred to as CO_2 production, is the net volume of excreted CO_2 measured at the mouth or airway, and is typically reported as the difference between expired and inspired CO_2 normalized to a complete minute and reported in ml/minute. $\dot{V}CO_2$ is computed by summing the product of the flow and CO_2 waveforms over the breath cycle. $\dot{V}CO_2$ is by convention reported at Standard Temperature and Pressure Dry (STPD) conditions. For breath-by-breath measurements it is calculated as:

$$\dot{V}CO_2 = \sum_{\text{breath}} FCO_2\,(t) * \dot{V}(t) * \Delta t$$

where FCO_2 (t) and $\dot{V}$(t) are the sampled individual values of the CO_2 and flow waveforms, which are multiplied together and summed over the entire breath and Δt is the sampling interval. The resulting per breath values are summed for all breaths in a minute or the per breath volume is multiplied by the respiratory rate to convert the CO_2 volume in a single breath to ml per minute.

In anesthesia and intensive care, components such as filters, HMEs, connecting tubes, elbows, airway adapters and suction adapters are placed between the endotracheal tube connector and 'Y' causing partial rebreathing and therefore increased amounts of inspired CO_2. Note that this inspired CO_2, if not accounted for, could result in an error in the calculation of $\dot{V}CO_2$ of several percent (Breen, 1996). More proximal placement of the sampling site will allow the end-tidal CO_2 value to better reflect the alveolar concentration. If the inspiratory carbon dioxide volume is ignored, the overestimation of $\dot{V}CO_2$ will increase with decreases in tidal volume and/or increases in apparatus deadspace.

It is important to note that the last portion of the alveolar plateau of the capnogram often considered to be the end-tidal PCO_2, is more likely the PCO_2 of the alveolar gas in the apparatus deadspace that is rebreathed in the next inspiration. This rebreathed gas does not contribute to the net pulmonary CO_2 elimination. Figure 1 illustrates the multiplication process with the plot of an actual waveform flow and CO_2 vs. time of a mechanical breath delivered in a volume control mode.

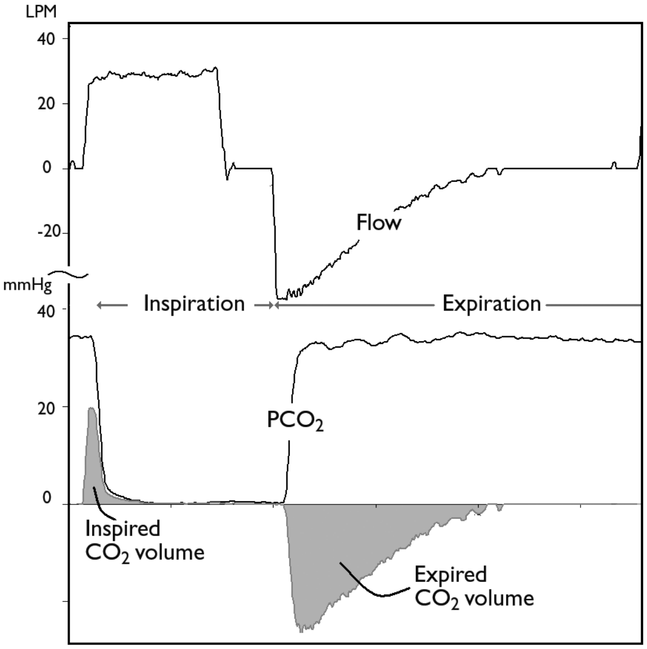

Figure 1 - Plot of flow and CO_2 waveforms for an individual ventilator delivered breath with product showing inspired and expired CO_2 volumes. LPM: liters per minute.

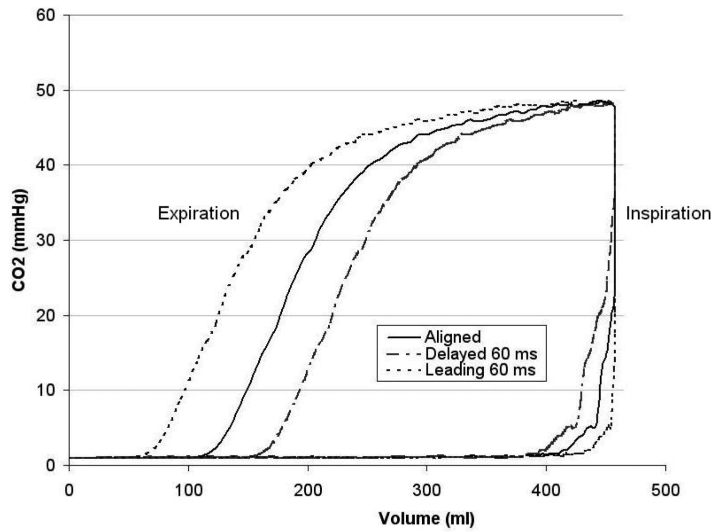

Figure 2 - Volumetric Capnogram showing both expiratory and inspiratory limbs and illustrating the effect of time misalignment. Note if the CO_2 waveform is delayed relative to the volume, the loop gets smaller on both ends, conversely when the CO_2 waveform is advanced relative to volume, the loop gets larger on both ends.

Note that due to apparatus deadspace from the sampling adapter, 'Y' and other circuit components, a small volume of end-expiratory CO_2 (from the previous breath) is rebreathed upon the initiation of inspiration. In this example (Figure 1), the expiratory CO_2 waveform rises rapidly to a plateau and the CO_2 volume curve follows that of the expiratory portion of the flow waveform. $\dot{V}CO_2$ would then be the difference between the expiratory and inspiratory areas of the dot-products between flow and CO_2. Now if we plot PCO_2 and volume instead (Figure 2), $\dot{V}CO_2$ the net volume of CO_2 eliminated, can be viewed as the area between the expiratory and inspiratory curves. With no rebreathing, the volume of CO_2 eliminated during a breath is the area under the volumetric capnogram. With rebreathing, the presence of inspiratory CO_2 must be accounted for when reporting and interpreting $\dot{V}CO_2$ (Breen, 1996).

PROXIMAL FLOW MEASUREMENT & COMPRESSION LOSS

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. The ventilator's "measured volume" is often displayed, but can be significantly higher than the actual delivered volume due to compression loss in the breathing circuit and compression volume in ventilator systems. While this is widely known, it is not fully appreciated (Tobin, 1994). 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. Compression volume losses come from two sources, the compressibility of the gas itself, and the expansion of the breathing hose in response to increased pressure. This wasted portion of the tidal volume, i.e. compression volume, does not ventilate the patient, but remains within the breathing circuit. 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, gas 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 is released and this additional volume is measured by sensors at the exhalation port of the ventilator. The release of stored energy in the distended and elongated breathing tubes adds even more to this additional measured volume. 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, 1994).

The correct conversion of the CO_2 signal from partial pressure to percent requires the PCO_2 signal to be divided by the total pressure (barometric + airway pressure). It is therefore critical that the pressure be measured at the same site as the CO_2 sample site.

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, the components used (humidifier, HMEs etc), and other assumptions, and are subject to error. Even with this correction applied, precise estimation of the compression volume can be challenging due to variations between individual breathing circuits, use of humidifiers, HMEs and other circuit components and dependencies on flow rate (Silvestri, 2006). Studies of several ventilators found that the discrepancy between displayed and proximally measured volume can vary significantly on the same ventilator if different brand breathing circuits are used (Bartel, 1985). 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 3). Thus, for 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.

Another potential source of volume measurement error is rain-out of humidified gases. Generally, expired gas is fully saturated with water vapor as it leaves the patient. By the time this expired gas reaches the expiratory flow meter in the ventilator, a portion of the water vapor has condensed, thereby reducing the measured expired gas volume. If rainout occurs, the % CO_2 increases. Resulting measurement errors will occur unless the flow and CO_2 are measured between the breathing circuit wye and the endotracheal tube.

Measuring expired flow and CO_2 as near to the patient as possible is ideal because the gas humidity and temperature can often be safely assumed at body temperature and pressure saturated (BTPS).

MAINSTREAM FLOW AND GAS MEASUREMENT

Proximal Flow and Gas Measurement (Respironics)

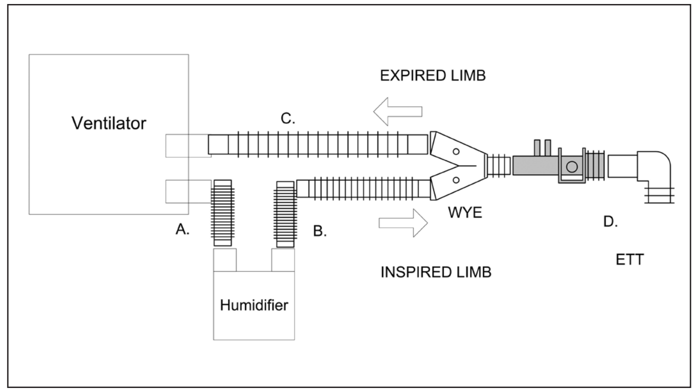

Figure 3 - Ventilator with breathing circuit with humidifier on inspiratory limb with proximal mainstream combined CO_2/flow sensor (grayed). Conditions at A through D are described below:

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 but less than or equal to 39 °C.

C. Gas returning from the patient has a lower partial pressure of water vapor due to condensation and a lower temperature (such as 33°C). (The relative humidity is still 100%, but the partial pressure of water vapor is lower.)

D. Gas expired at the patient's mouth is most likely slightly less than body temperature of nominally 37°C and fully saturated. If an unheated breathing circuit were to be used, the gas inspired at the patient's mouth would be less than the 35°C due to cooling during transport through as much as 8 feet of 15 mm ID breathing circuit tubing.

With robust mainstream sensors for flow and carbon dioxide located at, or very close to the same point in the gas stream (Figure 3), the principal issue is one of matching the frequency response of the two sensors. Issues of deadspace, resistance, and robustness to the challenging environment at the airway must also be kept in mind. Devices such as the combined CO_2/flow airway adapters from Respironics allow for minimizing the added deadspace between the wye and elbow and permit accurate measurement of carbon dioxide production and volumetric capnogram derived parameters such as Vd/Vt (Kallet et al., 2005).

Proximal Flow and Distal Gas Measurement

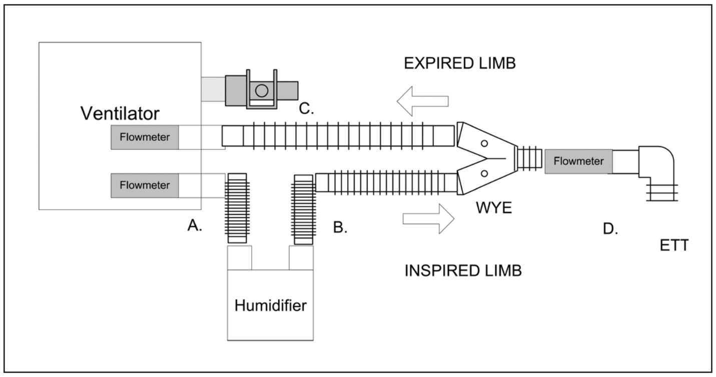

Figure 4 - Ventilator with breathing circuit with proximal mainstream flow sensor (grayed) and "mainstream" CO_2 sensor at exhalation port of ventilator (grayed).

Placement of the CO_2 sensor in the expiratory limb (Figure 4) eliminates the need to measure inspired CO_2 and account for rebreathing; however, standard capnometry is not possible when only expired gas is analyzed. In this configuration it is not possible to estimate functional anatomic dead space, or to calculate alveolar tidal and minute volumes. This configuration leads to over-estimation of CO_2 elimination because the expired volume and CO_2 read higher. The expired volume is higher because condensation has not occurred at the wye. CO_2 reads higher because it is measured after condensation.

Proximal Gas Measurement and Distal Flow Measurement

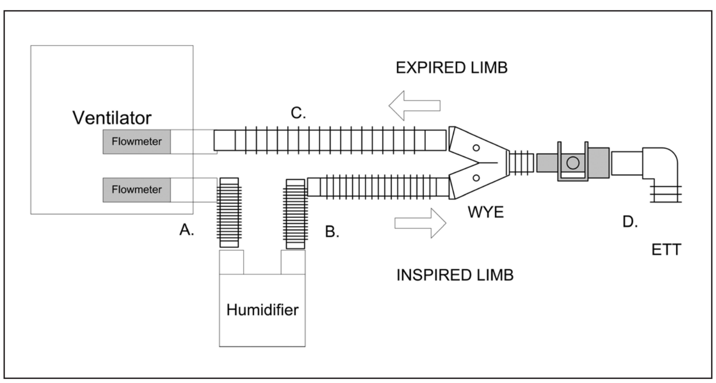

Figure 5 - Ventilator with breathing circuit with proximal mainstream CO_2 sensor (grayed) and flow sensors internal to ventilator (grayed).

If the sensors are separated, as with a mainstream CO_2 sensor used with separate flow sensors in the inspiratory and expiratory limb of the ventilator (Figure 5), the additional problems of correcting for the effects of different gas characteristics (temperature and humidity) and calibration issues associated with using separate sensors for inspiratory and expiratory flow must be considered. Fletcher (1983) evaluated the effects of a number of "potential and real sources of error" for the Siemens-Elema CO_2 Analyzer 930 which computed expired carbon dioxide volume using a mainstream CO_2 analyzer and a flow sensor in the expiratory limb of the ventilator. These sources of errors included rebreathing, effects of other gases, delays, and variations in temperature and water vapor. Rebreathing of gas in the tubing will cause $\dot{V}CO_2$ to be overestimated if not considered. Effects of other gases on the measurement depend upon the measurement method for flow and CO_2. Delay in carbon dioxide analysis is more of a consideration with sidestream systems, where proper frequency matching of the signals must be considered. Variations in temperature and vapor content of expired gas affecting volume correction and mixed expired fraction of CO_2 is more of an issue with sidestream systems than mainstream systems.

Note that while end-tidal values can be determined relatively accurately with proximal gas and distal flow measurements, volumetric capnogram based measurements are more challenging due to signal alignment issues, and sometimes manufacturers resort to using surrogates such as the expired volume at 50% of the end-tidal value for estimating airway deadspace.

Proximal Flow and Sidestream Gas Sampling

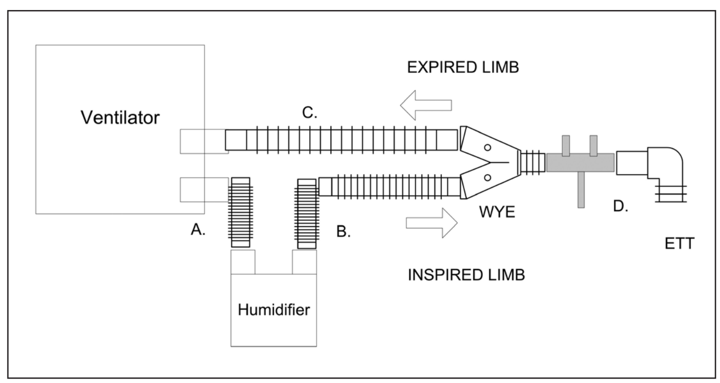

Figure 6 - Ventilator with breathing circuit with proximal mainstream flow sensor (grayed) and portion of sidestream gas sampling tube (grayed) shown.

When combining a proximal flow sensor with a sidestream CO_2 sensor (Figure 6), the issues associated with sidestream sampling must be addressed. The measurement of the partial pressure of a gas significantly distant from the sampling site raises a number of "laws of physics" issues including (1) water removal, (2) different conditions at the sampling site and sample cell (i.e. measurement site) in terms of temperature and humidity, (3) mixing of the sample gas as it is drawn through the sample cell, (4) variable pressure drop across the tubing and (5) dynamic distortions to the waveform (Epstein,1980). Delayed CO_2 measurement due to transit time through sampling tubes causes erroneous CO_2 partial pressure values due to unsynchronized airway pressure fluctuations. Condensation in the sample line can result in water blocking the sample line.

While some of these effects can be compensated for or corrected by other measurements or by the assumption of nominal values, other effects cannot. Within the sample tube itself, the dampening of the waveform occurs due to the effects of velocity profile and diffusion. (Epstein, 1980) Additionally, the sample flow rate may vary significantly as a function of a number of factors including the sample tube length (Schena, 1984), airway pressure, and the presence of an exhaust line occlusion.

When trying to combine a signal from flow sensor (proximal mainstream or within the ventilator) with a sidestream CO_2 signal, the potential for compounding of errors increases and the issues become much more complicated than with some of the other approaches. Investigators have pursued approaches ranging from simple corrections (Yamamoto et al., 1987; Noguchi et al., 1982) to more complicated non-linear approaches that have characterized the step response of the gas analyzer for each gas of interest and have corrected the measured signal with an inverted form of the step response function (Farmery & Hahn, 2000). Additionally, approaches have also been pursued using a mathematical model to correct for time compression due to effects of airway pressure on sample flow rates in positive pressure breathing systems (Farmery & Hahn, 2001). These corrections attempt to address some of the above errors, but while theoretically appealing, are complicated by clinical and manufacturing realities. The breathing circuit over time often accumulates secretions and other contaminants which are drawn into the sampling tube and measurement system. The specifications of sampling pumps which are stated as a nominal flow rate (often with a tolerance of ±10%) varies with time, load and between pump units. Increasing airway pressure compresses the gas in the sampling tube and raises the pressure drop across the tube changing the velocity of the gas in the tube. All these issues contribute to the difficulty in flow and CO_2 signal alignment.

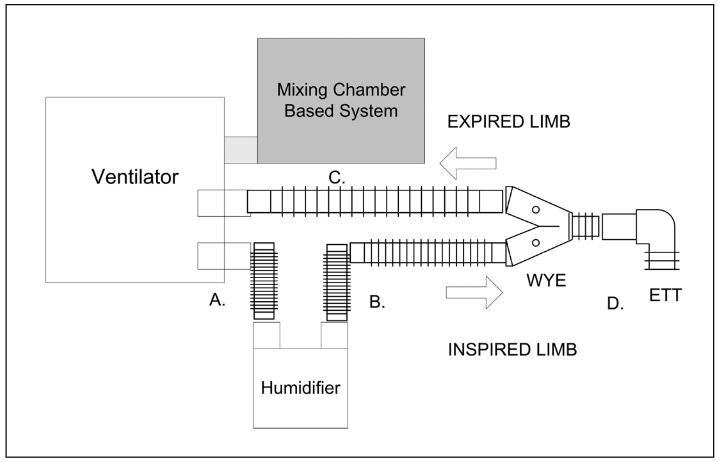

Figure 7 - Ventilator with breathing circuit with mixing chamber system (grayed) shown.

Mixing chamber based devices (Figure 7) are connected to the output of the ventilator (expiratory limb) and tend to be large in size and are often unable to offer breath-to-breath measurements. One approach to deal with the size issue is to divert a portion of the expired gas into a device known as bymixer (Rosenbaum et al., 2004) placed in the expiratory limb. The nature of the measurement does not permit end-tidal values to be determined and or any of the other parameters commonly associated with volumetric CO_2 analysis to be computed.

Mixing chamber systems have been considered clinical gold standard and give accurate and reliable measurements of $\dot{V}CO_2$. However, mixing chambers alone are incapable of measuring end-tidal CO_2, airway dead space, or any volumetric capnography parameters beyond $\dot{V}CO_2$.

Mixing chamber systems measure flow and CO_2 at the same location as the gas flows out of the mixing chamber so there are no problems with signal alignment, gas compression, condensation etc. Because flow is measured as it exits to ambient pressure, any pressure effects are also minimal.

CONCLUSION

Clinically acceptable results for volumetric gas measurements may be obtained with all of the configurations shown under the right favorable conditions if close attention is paid to the measurement, the equipment setup and interpretation of the displayed results. However, as more extremes of ventilator conditions in the critical care setting are encountered, only the proximal mainstream flow and gas measurement approach offers a solution that can provide reliable results under the wide ranging humidity values, pressures and temperatures seen in the clinical environment.

Table 1 - Sources of Error

	Compressibility Effects	Signal Alignment	Cooling Effects/Condensation	End-tidal CO_2 and Volumetric Capnography	Small Size, Ease of Use
Proximal Flow and Proximal Gas Measurement	1	1	1	1	1
Proximal Flow and Distal On-airway Gas Measurement	1	3	3	5	1
Proximal on-airway Gas Measurement and Distal Flow Measurement	3	3	5	3	1
Proximal Flow and Sidestream Gas Sampling	1	5	5	3	2
Mixing Chambers	1	1	1	4	5

1 = small effect; 5 = major effect

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