Accuracy of displayed volume with three airway sensors in an animal model

Mark J. Heulitt^{a,*}, Shirley J. Holt^b and Tracy L. Thurman^a

^a*Section of Critical Care Medicine, Department of Pediatrics, College of Medicine, University of Arkansas for Medical Sciences, Little Rock, AR, USA*

^b*Respiratory Care, Arkansas Children's Hospital, Little Rock, AR, USA*

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Abstract. Optimal mechanical ventilation in infants and pediatrics depends on the reliability of flow sensors to correctly measure flow and integrate it into accurately displayed tidal volumes (V_{TE}). However, reliability of these devices has not been established. We hypothesize that reliability would be affected by both the type of flow sensors and ventilator controllers utilized. Intubated, sedated Sprague Dawley rats ($n = 14$) were ventilated (control and support modes) utilizing two different ventilators: 1) fixed orifice flow sensor (FOF) and 2) both a hot wire (HWF) and variable orifice flow sensor (VOF), independently. Accuracy of delivered tidal volume was obtained by comparing the displayed volume of the different sensors to breath waveforms acquired using a heated 0–5 L/min calibrated pneumotachograph. Analysis was performed utilizing ANOVA with $P \leq 0.05$. Rats mean weight was 472 ± 46 g. For all modes, mean V_{TE} % difference was demonstrated across all three measuring sensors. For volume control ventilation and pressure control ventilation or time cycled pressure limited assist control, there was a difference between all three sensors. For pressure support ventilation, there was a difference with the HWF only. R-square values were FOF 0.80, HWF 0.54, and VOF 0.16. The accuracy of delivered V_{TE} is affected by both the flow sensor and ventilator controller to deliver the breath. We speculate that the flow sensor and the controller are associated with varying degrees of flow accuracy and control. We would expect volume accuracy for all modes to be equal if the flow accuracy were related to the inaccuracy of the flow sensors only.

Keywords: Pediatric, critical care, artificial, respiration, monitoring, ventilation

1. Introduction

Goals of modern mechanical ventilation in infants and children have focused on preventing over distention by limiting tidal volume (V_T), thus volutrauma [1–4]. Because of this, there is increasing emphasis on the value of monitoring respiratory function in ventilated patients. During recent years, ventilator technology has developed to allow continuous, in-line monitoring of

respiratory function. Ventilator displays of exhaled tidal volumes (V_{TE}) are traditionally used to indicate the delivered V_T for critically ill patients. Exact knowledge of both inspired and expired gas volumes with a sufficient level of precision is essential to optimize ventilator settings utilizing a lung protective technique. Little is known about the accuracy of the volumes displayed by conventional ventilators with flow sensors at the patient wye in this patient population. Optimal mechanical ventilation in infants and pediatrics depends on reliability of flow sensors to correctly measure flow and integrate it into accurately displayed delivered V_{TE} . It has been recommended in infants that an airway sensor be utilized to guarantee accuracy of volume measurements [5].

*Corresponding author: Mark J. Heulitt, Physiology and Biophysics, Critical Care Medicine, Arkansas Children's Hospital, 800 Marshall Street, Little Rock, AR 72202, USA. Tel.: +1 501 364 1858; Fax: +1 501 364 3188; E-mail: heulittmarkj@uams.edu.

However, reliability of these devices has not been established. We hypothesize that reliability would be affected by both the type of flow sensor and ventilator controller utilized.

2. Materials and methods

2.1. Animal model

The Animal Review Committee of the University of Arkansas for Medical Sciences approved this study. Animals were cared for in accordance with the standards for care and use of laboratory animals set forth by the University and the National Institutes of Health guidelines for principles of laboratory animal care. Fourteen adult male Sprague-Dawley rats mean weight 472 ± 46 g and two mechanical ventilators were utilized for these experiments: 1) Servo *i* (Maquet, Inc. Wayne, NJ); and 2) Avea (CareFusion Corp., San Diego, CA). All rats were sedated, intubated, and ventilated according to protocol. For the Servo *i* ventilator, a fixed orifice flow sensor (FOF) and three modes of ventilation: pressure control ventilation (PCV), volume control ventilation (VCV), and pressure support ventilation (PSV) were utilized. For the Avea ventilator, a variable orifice flow sensor (VOF) and heated wire flow sensor (HWF) were utilized with three modes of ventilation: volume assist control (V A/C), time cycled pressure limited assist control (TCPL A/C) and PSV. Other ventilator settings: set respiratory rate (when applicable) of 60 f, set V_T (when applicable) of 6–8 mL/kg, set peak inspiratory pressure (PIP) (when applicable) to get 6–8 mL/kg, FiO_2 was 25% and set positive end expiratory pressure (PEEP) of 2 cmH₂O. Rats were anesthetized with forane (3.5–4%) for approximately 2 min via a special inhalation mask and then an intravenous catheter was placed in the tail vein for supplemental anesthesia, a 3:1 mixture of etomidate (2 mg/mL) and fentanyl (0.05 mg/mL). Rats were then intubated with a 14-ga intravenous catheter with the needle removed. Rats were ventilated in a prone position. Gas humidification was maintained by an in-line Fisher & Paykel humidification system with temperature set at 37–39°C.

2.2. Data acquisition

Measurements of respiratory flow and pressure waveforms were acquired using the Biopac MP-100

System (Biopac Systems, Inc, Goleta, CA). A heated 0–5 L/min pneumotachograph (Hans Rudolph, Inc., Shawnee, KS) was placed in line, at the patient wye, between the endotracheal tube and the ventilator. Flow was calibrated using a calibrated flowmeter (Model TLO-15, Timeter Group, Lancaster, PA) and the appropriate FiO_2 . Volume measurements were obtained through the computer by integrating the flow signal. Volume was verified with a calibrated syringe (Hans Rudolph, Inc., Shawnee, KS). Pressure was calibrated with a water column manometer. All output signals were routed via an analog channel box into the Biopac MP100 data acquisition unit converting them into digital signals that can be processed with a computer. Signals were obtained at a rate of 1000 samples per sec.

2.3. Volume accuracy

Inspiratory tidal volume and V_{TE} were downloaded from the Servo *i* ventilator and compared to the data acquired from the pneumotachograph at the airway opening. Data downloaded from the Servo *i* ventilator were 10 consecutive breaths matched time-wise to the same 10 breaths collected from the pneumotachograph at the airway opening. Inspiratory tidal volume and V_{TE} were recorded (via video) from the Avea screen and compared to the data acquired from the pneumotachograph at the airway opening. Data recorded from the Avea screen were 10 consecutive breaths matched time-wise to the same 10 consecutive breaths collected from the pneumotachograph at the airway opening.

2.4. Analysis

Analysis was performed utilizing ANOVA with $P \leq 0.05$. Differences were calculated as displayed or set value – measured or true value. Percent difference (or error) was calculated as [(displayed or set value – measured or true value)/measured or true value]*100. Results are presented as mean $\pm$ SD and simple scatter plots. Pearson's correlation values are reported as a measure of agreement. Bland-Altman plots were constructed as the V_T difference versus the V_T mean between the ventilator displayed/set V_T and the V_T measured by the pneumotachograph at the airway. Bland Altman plots are given to show the level of agreement between volumes measured at the airway and that measured at the ventilator. The X-axis is the mean of the two

measurements as an estimate of the “true” value. The Y-axis is the difference of the two measurements; that is it shows the extent of disagreement. Ideally, the values should be scattered randomly and closely around zero. If one measure on average is above or below the other, there is a bias, and the mean of the differences will not be zero. If the scatter is not close to the mean, the SD, or precision, will not be small. Thus, the bias and precision are the mean and SD of the difference between volume measured at the airway and that measured at the ventilator. The bias and ± 2 SD are shown on the Bland-Altman plots for agreement.

3. Results

Rats mean weight was 472 ± 46 g. For each mode and sensor, mean V_{TE} % difference $\pm$ SD is shown in Table 1. For VCV and PCV (TCPL A/C), there was a difference between all three sensors ($P \leq 0.001$). For PSV, there was a decrease in V_{TE} % difference for the HWF only ($P < 0.001$). The V_{TE} % difference had significant variability depending upon the type of sensor utilized. The range of V_{TE} % difference was FOF

6.1–18.8%, HWF -0.8 to -7.1% and VOF 11.3 to 42.0%. Table 2 demonstrates the differences in $V_{TE} \pm$ SD as mL/kg for ventilator mode and sensor utilized. Again, there were significant differences by the type of sensor and mode utilized. For VCV, the V_{TE} difference was significantly less utilizing the HWF ($P \leq 0.001$). For PCV (TCPL A/C), there was a significant difference between all three sensors ($P < 0.002$). For PSV, the V_{TE} difference was increased between the FOF and HWF only ($P \leq 0.001$). For the FOF, the V_{TE} difference ranged between 0.3 to 1.48 mL/kg, HWF -0.1 to -0.47 mL/kg and VOF 0.45 to 1.76 mL/kg. Table 3 demonstrates the mean $\pm$ SD values for PIP, peak flow and mean airway pressure between modes and sensors utilized. For the VOF sensor, the greatest consistent variability was seen in PIP across all modes except PSV. These differences are consistent with volume errors demonstrated in Tables 1 and 2.

For volume differences, the R-square values from the Pierson Correlation Coefficient for the FOF was 0.80, HWF 0.54, and VOF 0.16. These values are consistent with the Bland Altman graphs Figures 1–3 where the greatest variability in volume accuracy is seen with the VOF flow sensor.

Table 1
Mean expiratory tidal volume % difference between sensors $\pm$ SD

Mode	Fixed orifice flow sensor (mean $\pm$ SD)	Mode	Hot wire flow sensor (mean $\pm$ SD)	Variable orifice flow sensor (mean $\pm$ SD)
Volume control ventilation	$18.8 \pm 12.7^*$	Volume assist control	$-0.8 \pm 8.9^*$	$37.9 \pm 35.6^*$
Pressure control ventilation	$6.1 \pm 10.2^{**}$	Time cycled pressure limited assist control	$3.2 \pm 9.3^{**}$	$41.8 \pm 34.7^{**}$
Pressure support ventilation	11.8 ± 11.1	Pressure support ventilation	$-7.1 \pm 8.2^{***}$	11.3 ± 32.0

*For volume control ventilation, there was a difference between all three sensors ($P < 0.001$).

**For pressure control ventilation (time cycled pressure limited assist control), there was a difference between all three sensors ($P < 0.001$).

***For pressure support ventilation there was a difference with the hot wire flow sensor only ($P < 0.001$).

Table 2
Mean expiratory tidal volume difference (mL)/kg $\pm$ SD

Mode	Fixed orifice flow sensor (mean $\pm$ SD)	Mode	Hot wire flow sensor (mean $\pm$ SD)	Variable orifice flow sensor (mean $\pm$ SD)
Volume control ventilation	1.48 ± 1.0	Volume assist control	$-0.10 \pm 0.6^*$	1.45 ± 1.2
Pressure control ventilation	$0.30 \pm 0.5^{**}$	Time cycled pressure limited assist control	$-0.21 \pm 0.5^{**}$	$1.76 \pm 1.4^{**}$
Pressure support ventilation	0.79 ± 0.7	Pressure support ventilation	$-0.47 \pm 0.6^{***}$	0.45 ± 1.4

*For volume control ventilation, there was a difference with the Hot wire flow sensor only ($P < 0.001$).

**For pressure control ventilation (time cycled pressure limited assist control), there was a difference between all three sensors ($P < 0.002$).

***For pressure support ventilation, there was a difference with the fixed orifice flow sensor only ($P < 0.001$).

Table 3
Mean $\pm$ SD for peak inspiratory pressure (cmH₂O), peak flow (mL/sec), and mean airway pressure (cmH₂O)

Features	Mode	Fixed orifice flow sensor (mean $\pm$ SD)	Mode	Hot wire flow sensor (mean $\pm$ SD)	Variable orifice flow sensor (mean $\pm$ SD)
Peak inspiratory pressure	Volume control ventilation	13.4 $\pm$ 1.6*	Volume assist control	10.3 $\pm$ 1.0*	9.1 $\pm$ 1.8*
Peak flow	Volume control ventilation	16.1 $\pm$ 3.4**	Volume assist control	10.8 $\pm$ 3.0	9.4 $\pm$ 3.7
Mean airway pressure	Volume control ventilation	5.5 $\pm$ 0.4***	Volume assist control	4.3 $\pm$ 0.3	4.0 $\pm$ 0.5
Peak inspiratory pressure	Pressure control ventilation	9.1 $\pm$ 1.0	Time cycled pressure limited assist control	9.3 $\pm$ 1.9	7.9 $\pm$ 1.9*
Peak flow	Pressure control ventilation	15.2 $\pm$ 2.7**	Time cycled pressure limited assist control	11.6 $\pm$ 2.9	10.0 $\pm$ 3.6
Mean airway pressure	Pressure control ventilation	4.8 $\pm$ 0.4***	Time cycled pressure limited assist control	3.9 $\pm$ 0.6	3.7 $\pm$ 0.6
Peak inspiratory pressure	Pressure support ventilation	10.5 $\pm$ 2.4*	Pressure support ventilation	8.6 $\pm$ 2.3	8.3 $\pm$ 2.7
Peak flow	Pressure support ventilation	19.9 $\pm$ 4.4**	Pressure support ventilation	16.1 $\pm$ 2.5	14.9 $\pm$ 2.9
Mean airway pressure	Pressure support ventilation	3.8 $\pm$ 0.7	Pressure support ventilation	3.8 $\pm$ 0.5	3.8 $\pm$ 0.6

*For peak inspiratory pressure, all sensors were different for volume control ventilation ($P < 0.030$), variable orifice flow sensor for pressure control ventilation ($P = 0.024$), and fixed orifice flow sensor for pressure support ventilation ($P < 0.044$).

**For peak flow, fixed orifice flow sensor was different for volume control ventilation ($P < 0.002$), pressure control ventilation ($P < 0.007$), and pressure support ventilation ($P < 0.009$).

***For mean airway pressure, fixed orifice flow sensor was different for volume control ventilation ($P < 0.020$) and pressure control ventilation ($P < 0.001$).

Fig. 1. Bland-Altman plots were constructed as the V_T difference versus the V_T mean between the ventilator displayed/set V_T and the V_T measured by the pneumotachograph at the airway. Zero (solid line), mean (small dash) and ± 2 SD (long dash) are shown. FOF = Fixed Orifice Flow Sensor, VCV = volume control ventilation, PCV = pressure control ventilation, PSV = pressure support ventilation.

Fig. 2. Bland-Altman plots were constructed as the V_T difference versus the V_T mean between the ventilator displayed/set V_T and the V_T measured by the pneumotachograph at the airway. Zero (solid line), mean (small dash) and ± 2 SD (long dash) are shown. VOF = Variable Orifice Flow Sensor, VCV = volume control ventilation, PSV = pressure support ventilation, TCPL = time cycled pressure limited.

Fig. 3. Bland-Altman plots were constructed as the V_T difference versus the V_T mean between the ventilator displayed/set V_T and the V_T measured by the pneumotachograph at the airway. Zero (solid line), mean (small dash) and ± 2 SD (long dash) are shown. HWF = Hot Wire Flow Sensor, VCV = volume control ventilation, PSV = pressure support ventilation, TCPL = time cycled pressure limited.

4. Discussion

Accuracy is the ability of a measuring device to capture the true value of a measure. Accuracy is usually expressed as a percentage of the full scale. Precision is the ability of a measurement to be consistently reproduced. Both of these features would be essential in ventilating infants and children when the amount of V_T delivered may be directly related to incidence of ventilator induced lung injury. The accurate delivery of V_T to mechanically ventilated infants and children is essential to ensure that volumes do not exceed those desired by the clinician. The principal observation in our study is that the accuracy of delivered V_{TE} is affected by both the flow sensor and ventilator controller to deliver the breath. We speculate that the flow sensor and the ventilator controller are associated with varying degrees of flow accuracy and control. We would expect volume accuracy for all modes to be equal if the flow accuracy were related to the inaccuracy of the flow sensors only. In this study, we chose to utilize the three most popular types of pneumotachographs utilized in the clinical critical care environment. These pneumotachographs offer the advantage to the manufacturer of a cheaper, easily manufactured option that should be reliable in most clinical scenarios. These differential pressure flow sensors

incorporate some type of restriction (point orifice, variable flap or annular obstruction target or linear flow) restriction that generates a pressure difference across the sensor. Flexible tubing to either side of the flow obstruction transmits the differential pressure signal to a sensitive pressure sensor located inside a monitor. Factors that influence the measurement of flow for this type of sensor include the gas molecular weight, temperature and airway pressure. Of the three types of flow sensors included in this evaluation, the variable orifice flow sensor has the advantage of an improved immunity to artificial flow signals caused by moisture and secretions in breathing circuits. These flow sensors use a flexible sheet material to create an opening that is small when flow is low and wider when flow increases. This dynamically changing orifice theoretically has a more linear relationship between differential pressure and flow. The variable orifice type of flowmeter's accuracy depends, however, upon the consistent stress-strain characteristics of the variable orifice flap, which can be degraded by inter-device or intra-device variations created during the manufacturing or intra-device changes due to fatigue during long-term use. As can be seen in the reliability data in our study, the VOF sensor had the greatest variability as compared to the other sensors. The fixed orifice pneumotachograph utilizes a narrowed orifice where pressure difference measured across the orifice in general is proportional to the square of the flow measured. In this design, microprocessors can be programmed to store the parameters of these flow sensors to compensate for a non-linear pressure-flow relationship. Recent advances in this technology have improved its ability to measure very low flow reliably. The heated wire anemometer is the third type utilized in the study. These are also known as hot wire or hot element anemometers. These thermal flow sensors are based on convective heat exchange taking place when the gas flow passes over the heated sensing element. The main advantages of thermal flow sensors are high sensitivity and the wide measurement range. The drawbacks of many thermal flow sensors are substantially related to the non-linearity of the calibration curve: although it could represent a valuable characteristic because of the abovementioned high sensitivity at low flow rates. On the other hand, non-linearity causes an appreciable sensitivity decrease with fluid flow. Another important variable in accuracy in the measurement of V_{TE} to mechanically ventilated infants and children is the location of the sensor. 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 in what the ventilator reports as delivered due to the wasted compression volume. This wasted portion of the V_T 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 must be made for this effect that is proportional to the inspired peak pressure. In previous studies in both animals and patients, we have demonstrated that the use of circuit volume compression compensation can be accurate; however, all volume must be accounted for in a pre-use measurement of the system [6,7]. The compression factor assigned by the manufacturer for the circuit is not adequate in calculating compression volume loss since there is volume loss to the internal tubing of the ventilator and humidification system that must be compensated for to ensure the measured volume delivered is accurate. A potential limitation of our study may be associated with our healthy animal model. Since patients with respiratory compliance and resistance can affect the accuracy of measured volumes [8], then our results may be influenced in an experimental model utilizing a sick animal. However, in this study, we chose to examine the accuracy of small V_T utilizing three different types of airway sensors to demonstrate that differences exist even in healthy animals. Another limitation is the length of our study. Since degradation of the reliability of any of the sensors could be expected with prolong use, the differences we have demonstrated may be more exaggerated with a longer exposure to heat, humidity and the animal's secretions.

In conclusion, our results are that the accuracy of delivered V_{TE} is affected by both the flow sensor and

ventilator controller to deliver the breath. We speculate that the flow sensor and the ventilator controller are associated with varying degrees of flow accuracy and control. We would expect volume accuracy for all modes to be equal if the flow accuracy were related to the inaccuracy of the flow sensors only.

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