Accuracy of small tidal volume measurement comparing two ventilator airway sensors

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Received 15 November 2012

Revised 1 December 2012

Accepted 4 January 2013

Abstract. Goals of modern mechanical ventilation in infants focus on preventing over-distention by limiting tidal volume. Accurate measurement of these volumes is essential. We hypothesized that tidal volume accuracy differs dependent upon the type of airway sensor utilized in tidal volumes less than 10 mL. Intubated, sedated Sprague Dawley rats ($n = 40$) were ventilated utilizing both control and support ventilator modes. Accuracy of volume delivery was compared between a fixed orifice flow sensor (FOF) and a hot wire anemometer (HWA) to a Hans Rudolph linear pneumotachograph positioned at the patient wye. Rats median weight was 476 grams (range 370–544), tidal volume (V_T) 3.5 mL (1.2–11.4), f 50 (18–102), and PIP 9.5 cm H_2O (1–34). Across all modes, bias and precision were HWA -0.76 , 1.09 ; FOF 0.22 , 0.61 . This study confirms that there are differences in the accuracy of small tidal volumes measured with a FOF as compared to a HWA. Utilizing a FOF, control modes exhibit improved precision and decreased bias as compared to support modes.

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

1. Introduction

It has been recommended that the only site to obtain accurate volume measurements is at the airway opening in infants and children [1,2]. However, there is limited knowledge of the accuracy of these devices utilized on mechanical ventilators with tidal volumes (V_T) of less than 10 mL. In order to measure volumes at the airway, a pneumotachograph (PNT) must be positioned at the patient's airway opening or endotracheal tube. Unfortunately, this technique has disadvantages, especially in infants and children. Pneumotachography at the airway opening is associated with increased dead space most notably in infants with low V_T [3]. In addition,

a PNT positioned at the airway opening may be associated with impaired admittance to the endotracheal tube and airways, increased contamination of the PNT, and an increased risk of extubation due to the weight of the PNT.

The objective of our study was to determine if the accuracy of measured V_T utilizing small tidal volumes differed dependent upon the type of airway measuring sensor utilized.

2. Materials and methods

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.

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For this study, intubated, sedated Sprague Dawley rats ($n = 40$) were ventilated utilizing both control and support ventilator modes. Accuracy of volume delivery was compared between a fixed orifice flow sensor (FOF) and a hot wire anemometer (HWA) to a Hans Rudolph linear PNT positioned at the patient wye.

2.1. Animal preparation

All rats were sedated with a mixture of etomidate (6 mg/mL) and fentanyl (0.05 mg/mL) (3:1) through an initial intra-peritoneal (IP) injection, dosed according to their weight (0.4 mL/50 g) and supplemental anesthesia was administered via an intravenous (IV) catheter placed in the tail vein. The sedation was given incrementally with repeated doses until the animal was unconscious, but breathing spontaneously. Absence of foot-withdrawal upon pinching was used to indicate suitable plane of anesthesia. Rats were then intubated using an otoscope with a modified ear speculum used as a laryngoscope. A thin flexible stylet wire was placed through the vocal cords and the endotracheal tube threaded on the wire and placed through the vocal cords. The wire was then removed leaving the endotracheal tube in place. The endotracheal tube was a 5.5 cm-long, 16 gauge IV catheter, with the needle removed.

2.2. Equipment setup

For the ventilator utilizing the FOF (Servo *i*, Maquet, Inc. Wayne, NJ), measurement of system compliance was calculated during calibration of all sensors and actuators as part of the pre-use check of the ventilator. As part of the pre-use check, the patient circuit, with the flow sensor in line, was attached and the patient wye blocked. The system was then checked for leakage. A “pass” was given if leakage was less than 80 mL/min. Pressure sensors were then checked for zero, after which the circuit was pressurized up to 50 cm H₂O for 250 ms, and flow was integrated. Pressure was then maintained for two seconds in order for thermal effects to equilibrate. Additional flow was integrated and then added to the previously measured volume. The compliance factor was then calculated $K_c = \frac{d_v}{(P_1 - P_0)}$ mL/cm H₂O, where K_c is the compliance factor, d_v is the total integrated volume, and P_0 and P_1 are start and target pressure. The compliance factor thus obtained was used for calculation of measured exhaled volumes during pressure dependant modes of ventilation.

For the ventilator utilizing the HWA (Drager Babylog 8000TM, Drager, Lubeck, Germany), there was no method within the ventilator to measure system compliance. The HWA flow sensor was calibrated by blocking the flow sensor attached to the ventilator circuit and initiating the ventilator flow sensor calibration internal software algorithm. It was deemed calibrated when the “flow sensor calibrated” message appeared on the ventilator screen.

2.3. Data acquisition

Rats were studied utilizing methods previously described by Heulitt et al. [4] with the Biopac MP-100 (Biopac Systems, Inc., Camino Goleta, CA) data acquisition system. Signals were obtained at a rate of 1000 samples per second. Volumes were verified with a 10 mL calibrated syringe (Hans Rudolph, Inc., Shawnee, KS) at 2, 4 and 10 mL. A heated, 0–5 L/min PNT (Hans Rudolph, Inc., Shawnee, KS) was utilized for all experiments. PNT dead space was 0.72 mL. The ventilator circuits used were Fisher & Paykel RS-232 (Fisher & Paykel Healthcare Inc., Irvine, CA). Gas humidification was maintained by an in-line Fisher & Paykel MR850 humidification system (Fisher & Paykel Healthcare Inc., Irvine, CA). The compressible volume amount, according to manufacturer specifications, was 0.79 mL/cm H₂O for the circuit.

All rats were ventilated with both the FOF ventilator and the HWA ventilator. For the FOF ventilator, the infant sensor was utilized in Pressure Regulated Volume Control (PRVC), Volume Support ventilation (VSV), Volume Control ventilation (VCV), and Pressure Control ventilation (PCV). Circuit compliance compensation software was activated in all modes. For the HWA ventilator, the flow sensor for neonates was utilized in Pressure Support Ventilation (PSV), Synchronized Intermittent Mandatory Ventilation-Pressure Control (SIMV-PC), and SIMV-PC+ Volume Guarantee (VG). The rats were ventilated at breath rate of 50 bpm in all control modes, a V_T of 6 mL/kg in volume modes, and in pressure modes, the inspiratory pressure level was set to deliver a V_T of 6 mL/kg, Positive end-expiratory pressure (PEEP) levels of 0 and 2 cm H₂O, and FiO₂ between 0.25 or 0.30. Variable inspiratory flow and variable expiratory flow (VIVE) was utilized for HWA experiments. With VIVE on, the continuous expiratory flow can be changed independent of the continuous inspiratory flow. Inspiratory VIVE was set between 3–6 L/min and expiratory VIVE was set between 5–8 L/min.

For each experiment, the PNT was inserted between the endotracheal tube and wye piece of the ventilator circuit, and gas flow and pressure measurements were obtained for thirty seconds. Flow and pressure waveforms obtained with the PNT at the airway were analyzed for peak inspiratory flow (PIF), peak inspiratory pressure (PIP), slope of inspiratory flow (slope), and expiratory tidal volume (V_{TE}). Values for V_{TE} displayed by the ventilators were compared to measurements obtained with the PNT at the airway. Displayed measurements were downloaded from the ventilator (FOF) via a memory card, or manually recorded from the ventilator screen (HWA). Ten consecutive breaths (ventilator displayed) were matched time-wise and compared to the same 10 breaths collected from the PNT at the airway opening.

2.4. Statistical methods

To measure the agreement between the measured PNT and the ventilator displayed V_{TE} we calculated Pearson's correlation coefficient and concordance correlations. We present the overall correlations for both sensor types (FOF and HWA) as well as for each individual mode of ventilation. Weighted correlations are reported. For Pearson's correlation coefficient a value of zero indicates that there is no association between the two variables. There are no published levels of acceptance for agreement in clinical studies utilizing concordance

correlations; however, in published reviews on interobserver agreement, it was expressed that an agreement of greater than 90% represented excellent agreement [5,6]. In addition, Bland and Altman [7,8] plots were constructed as the difference (ventilator displayed V_{TE} – PNT measured V_{TE}) versus the V_{TE} mean of the two measures. A nonparametric test, Wilcoxon Signed Ranks test, was utilized to compare PIF, PIP and slope. Comparisons were made between the two support modes (VSV and PSV), PRVC and SIMV-PC+VG, and between PCV and SIMV-PC. A P value of 0.05 was considered significant.

Data analyses were generated using SAS®/Stat software, Version 9 of the SAS System for Windows, SAS Institute Inc., Cary, NC. Plots were constructed using SPSS® version 13.0 for Windows, SPSS Inc., Chicago, IL.

3. Results

Forty male Sprague Dawley rats were utilized for this study. Median (range) weight was 476 g (370–544 g). Median (range) values for PIF, PIP, and slope are reported in Table 1. When comparing the two support modes (VSV and PSV), PIF and PIP were higher for the FOF ($P < 0.0001$) than with the HWA. When we compared PRVC and SIMV-PC+VG, we found that PIF was higher for the FOF than the HWA ($P < 0.0001$). PIF was less for the FOF than the HWA when comparing PCV and

Table 1
Median (range) values for peak inspiratory flow, peak inspiratory pressure and inspiratory slope

Sensor	Mode	Peak inspiratory flow (mL/sec)	Peak inspiratory pressure (cm H ₂ O)	Slope (mL/sec/sec)
Fixed orifice flow	Pressure control ventilation	18 (10–34)*	8 (7–12)	124 (34–329)**
	Pressure regulated volume control	26 (14–39)***	9 (7–14)	207 (63–504)
	Volume control ventilation	13 (7–16)	10 (7–18)	40 (18–101)
	Volume support ventilation	32 (19–46)**	14 (2–22)**	109 (59–225)
Hot wire anemometer	Synchronized intermittent mandatory ventilation- Pressure control + volume guarantee	22 (12–31)***	9 (6–13)	186 (62–293)
	Pressure support ventilation	23 (14–34)**	8 (3–11)**	123 (47–257)
	Synchronized intermittent mandatory ventilation- Pressure control + volume guarantee	21 (14–30)*	8 (7–11)	187 (71–324)**

For peak inspiratory flow (* $P < 0.01$; ** $P < 0.0001$; *** $P < 0.0001$).

Peak inspiratory pressure (** $P < 0.0001$).

Slope (** $P = 0.001$).

SIMV-PC ($P = 0.01$), and inspiratory slope was also less for the FOF than the HWA ($P = 0.001$).

Weighted Pearson's correlation and concordance correlation are reported for V_{TE} in Table 2. For the FOF, Pearson's correlation values were higher than those for the HWA. The same was true for concordance correlation.

Figures 1 and 2 show Bland-Altman plots for both the FOF and HWA sensors for the various modes of ventilation. The difference, or bias, is calculated as the mean difference (mL) in the ventilator displayed V_{TE} and the PNT V_{TE} , and precision is the variance, or standard deviation. With Bland-Altman plots, we

expect to see random scatter about zero (i.e., no difference between the measurements from the two methods) and uniform variability throughout the range of measurements. In Fig. 1 for the FOF, the mean difference (bias) is positive and is close to the zero difference line. Most values fall within ± 2 SD with VSV mode having more scatter as V_{TE} increased. In Fig. 2 for the HWA, the mean difference (bias) is negative and is further off the zero difference line than with the FOF. However, as with the FOF, most values fall with ± 2 SD. PSV had the most scatter; although, unlike the FOF and VSV, the scatter seen with PSV and the HWA does not increase with V_{TE} .

Table 2
Correlations (weighted) for expiratory tidal volume

Sensor	Mode	Pearson's correlation	Concordance correlation
Fixed orifice flow	Pressure control ventilation	0.50	0.49
	Pressure regulated volume control	0.74	0.71
	Volume control ventilation	0.70	0.67
	Volume support ventilation	0.86	0.79
Fixed orifice flow-All modes		0.82	0.77
Hot wire anemometer	Synchronized intermittent Mandatory ventilation-Pressure control + volume guarantee	0.19	0.08
	Pressure support ventilation	0.25	0.17
	Synchronized intermittent mandatory ventilation-pressure control	0.06	0.04
Hot wire anemometer-All modes		0.28	0.16

Fig. 1. Bland-Altman - plot constructed as the expiratory tidal volume (V_{TE}) difference versus the mean of the two measures; zero (solid), mean difference (small dashes), and ± 2 SD (long dashes) lines are included. Modes were Pressure Control ventilation (PCV), Pressure Regulated Volume Control (PRVC), Volume Control ventilation (VCV), and Volume Support ventilation (VSV). Fixed Orifice Flow Meter (FOF).

Fig. 2. Bland-Altman - plot constructed as the expiratory tidal volume (V_{TE}) difference versus the mean of the two measures; zero (solid), mean difference (small dashes), and ± 2 SD (long dashes) lines are included. Modes were Synchronized Intermittent Mandatory Ventilation-Pressure Control + Volume Guarantee (SIMV-PC + VG), Pressure Support Ventilation (PSV), and SIMV-PC. Hot Wire Anemometer (HWA).

4. Discussion

The measuring of volume in mechanically ventilated infant and pediatric patients may result from incorrect data processing and numerical integration and thus a lack of precision of flow measurements. A main source of volume error may be the magnitude of the flow signal, since the mean airflow is the product of volume and respiratory rate. Therefore, the measuring error of small-ventilated volumes commonly decreases with increasing respiratory rate because with a constant volume, an increase in respiratory rate equals an increase in air flow [9]. In our experiments, respiratory rate and volume were constant through the experiments and consistent with those expected in the ventilation of a neonate.

There have been no published recommendations regarding acceptable accuracy of V_T delivered to neonatal patients. Two important questions must be answered for the clinician. First, what is the level of precision expected for delivered V_T in mechanically ventilated neonates? This is a difficult question since there is still debate over how much V_T induces lung injury. In our study, we utilized a desired precision of volume measurement of at least 10% of set volume. Second, if a technology demonstrates an improvement in the accuracy of volume measurement, is the better precision worth any risks associated with the enhanced

technique. This is the question regarding use of an airway sensor. In this study with small volumes, we have demonstrated that precision is improved with the utilization of an airway sensor. However, the use of this sensor, especially in small patients, may be associated with certain risks such as increased dead space, impaired admittance to the endotracheal tube, and increased risk of extubation. We have previously examined the use of circuit compression volume compensation as an alternative way to ensure the adequacy of volume accuracy [4,10]. However in these studies, we did not use volumes less than 10 mL, and thus, we must be cautious in recommending its use in such small tidal volumes.

The major limitation of this study is our use of an animal model with normal lungs. We felt it was important to examine the accuracy in an animal model with normal compliance and resistance to demonstrate the volume accuracy of these devices. Any differences noted should be exaggerated further in a model of a sick lung. However, it is essential to note that despite the use of animals with healthy lungs, there were significant differences found between measuring devices and modes utilized. It should be further noted that there could be significant variability of the accuracy of measuring devices since there is no standard amongst manufacturers for the design and implementation of these devices.

In conclusion, accurately measuring V_T in mechanical ventilators of infants and children has been advocated, especially when using low V_T and low stretch approaches. The results of our study confirm that there are differences in the accuracy of small V_T measured with a FOF sensor as compared to a HWA. Utilizing a FOF sensor, control modes exhibit improved precision and decreased bias as compared to support modes.

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