Mechanical ventilator flow and pressure sensors: Does location matter?

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Abstract

Introduction
Accurate measurements of parameters are essential during mechanical ventilation support. These measurements are achieved through sensors that monitor flows, volumes and pressures. External and internal flow sensors are both commonly used in mechanical ventilation systems to measure gas entering and leaving the lungs. The sensors could be located outside the ventilator (external or proximal) or inside the ventilator (internal or distal), each of which have their own respective advantages and disadvantages. There are differences in the way they function and the information they provide, which can affect their accuracy and usefulness in different clinical situations. The purpose of this study was to examine the differences between two critical care ventilators utilizing external sensors to two other ventilators utilizing internal sensors.
Methods
A bench study using a lung simulator was conducted using three passive, single compartment models: 1) compliance of 40 ml/cmH_2O, resistance of 10 cmH_2O, 2) compliance of 40 ml/cmH_2O, resistance of 20 cmH_2O, and 3) compliance of 20 ml/cmH_2O, resistance of 10 cmH_2O. In each study, two different modes of ventilation, volume controlled (tidal volume 400 ml, respiratory rate 20, PEEP 5 cmH_2O, inspiratory time 0.7 seconds) and pressure controlled (inspiratory pressure 15 cmH_2O, respiratory rate 20, PEEP 5 cmH_2O, inspiratory time 0.7 seconds) were tested. We compared the inspiratory flow, inspiratory tidal volume, peak inspiratory pressures and PEEP in four commercially available critical care ventilators. Two use external flow sensors: G5 (Hamilton Medical), Bellavista 1000e (Vyaire Medical), and two use internal flow sensors: Evita Infinity 500 (Drager), and PB 980 (Medtronic). We also compared these parameters to a mathematical model.
Results
There were statistically significant differences ($P < 0.001$) in all four measured parameters: inspiratory flow, tidal volume, PIP and PEEP between all four ventilators, and between the mathematical model and all four ventilators in both modes, in all three clinical scenarios. The post-hoc Dunn test showed significant differences between each ventilator, except for a few parameters in PIP and PEEP, but not in flow or volume. There were variable but significant differences between some of the four parameters measured from the ventilator compared to those measured from the simulator of all four ventilators in both modes. The two ventilators using external sensors had more accurate differences between the delivered and measured tidal volumes ($P < 0.001$) and inspiratory flow ($P < 0.001$), however, the other two ventilators with internal sensors had more accurate differences between the delivered and measured PIP ($P < 0.001$) and PEEP ($P < 0.001$) levels.
Conclusions
All four ventilators performed differently from each other and from the mathematical model. The two ventilators using external sensors had more accurate differences between the delivered and measured tidal volumes and inspiratory flow, the two ventilators with internal sensors had more accurate differences between the delivered and measured PIP and PEEP levels. Differences between the ventilators depend on multiple factors including location, type of sensor, and respiratory mechanics.

Keywords: Flow sensor, Pressure sensor, PIP, PEEP, Tidal volume, Flow

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Quick look

Not all ventilators behave similarly regarding accuracy of measurements and delivery of flow, volume, and pressure.

Introduction

Mechanical ventilators employ various sensors to monitor their effects on the patient in real time. The accuracy of such measurements is crucial for supporting the most favorable patient outcomes. Many of the key parameters observed by clinicians are collected through flow and pressure sensors that are in contact with the gas delivered to the patient. Govoni [1] and Chatburn [2] previously identified discrepancies in expected accuracies of ventilators, particularly in volume-related measurements.

Flow is typically measured through a type of transducer that is able to detect a physical feature of the gas being provided to the patient. The two most common types are hot wire anemometry and orifice flowmeters (Figure 1). Hot wire anemometry involves measuring the degree to which the flow of gas cools a portion of the sensor. [3] Two probes with a conductive wire between them are placed in contact with the gas as a current is sent through the wire to heat it. The flow of gas removes heat from the wire, altering its resistance. This change in resistance is detected by measuring voltage or current which reflects a nonlinear relationship to flow rate. Orifice flowmeters traditionally function by creating a constriction in the flow of gas within the tube. Typically created with a narrowing in the tubing, these flowmeters create a differential pressure gradient that adheres to Bernoulli's principle. [3] Gas flowing through this narrowed cross section increases pressure in a non-linear fashion to flow. Variable orifice flowmeters, like orifice flowmeters, also create a differential pressure to create a flow restriction used in measurement. [4] Instead of a cross-sectional reduction in area, the device consists of an orifice plate, which is typically a moveable flap and is placed within the tube containing the gas. [3] As gas flows through, the flap is pushed and enlarges the area through which gas can pass, thus increasing flow rate. Unlike orifice flowmeters, the displacement of the flap creates a linear relationship between the differential pressure and the flow. Advancement of microelectronics has compensated to account for non-linear data sampling which maintains an indistinguishable accuracy when compared to linear data. [5]

Pressure is often measured through pressure transducers in contact with the flow of gas to the patient. [5] These transducers typically utilize a piezoresistive strain gauge that contains a malleable resistor that changes its resistance in response to a change in length. Wheatstone bridges are a common circuit used to take advantage of this malleable resistive feature to produce a calibrated voltage change. [6] This subsequent voltage change is then converted to a value in pressure with a non-linear relationship. An inductive transducer is another popular method of pressure measurement, where an inductive coil is used to generate flux in a magnetic field from the physical movement of a conductive element. [7] The diaphragm experiences a deformation from the force of gas pressure which affects the inductance of the diaphragm.

Ventilators typically employ these sensors externally or internally. External sensors are positioned along the Y-tube connector and are considered to be proximal to the patient. Internal sensors are positioned inside the ventilator and are then considered to be distal to the patient. There are advantages and disadvantages for both proximal and distal sensors. Proximal sensors measure the flow and pressure close to the patient and are not affected by circuit compliance, ventilator valves, and may provide faster detection of respiratory signals, but are exposed to the harsh environments of secretions and humidity and are not reusable, which might affect costs of patient care. On the other hand, distal sensors are protected inside the ventilator, but can be affected by circuit compliance, resistance, and ventilator valves, and don't need to be changed per patient use. Existing literature presents mixed results in attempts to compare the accuracy of externally and internally located sensors. Studies conducted on both infant and adult ventilators have suggested that external sensors exhibit greater accuracy when measuring volume-related parameters. [8,9] On the contrary, Motta-Ribeiro et al. found that internal sensors may be more effective at measuring volume and pressure at certain ventilatory settings. [10]

The aim of this bench study was to further elucidate the variation in ventilator accuracy and evaluate the effect that sensor location may exert on said variation.

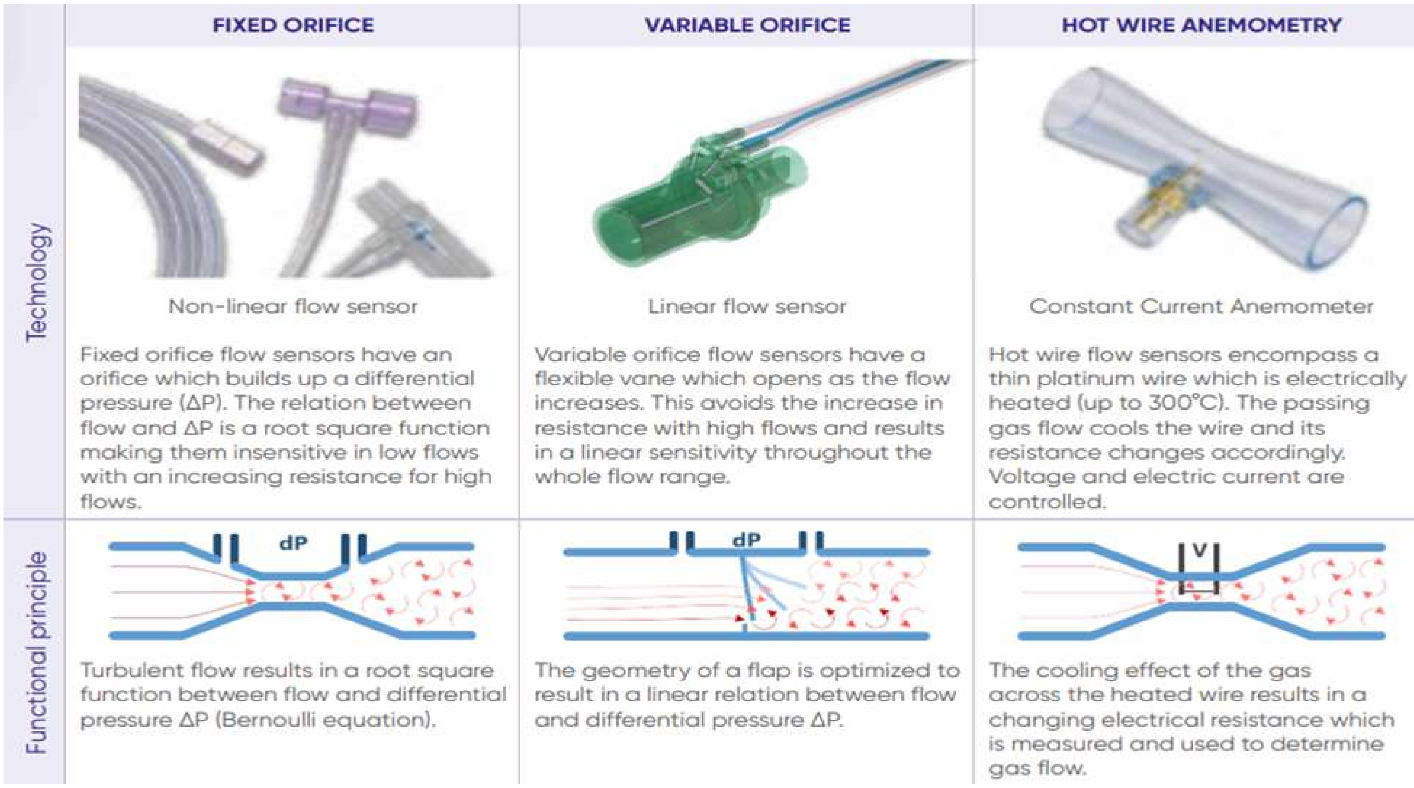

Figure 1: Different types of flowmeters. (From Vyaire Medical, with permission)

Methods

This bench study was conducted at Kuakini Medical Center, Honolulu, Hawaii. A dual adult lung simulator (Training Test Lungs, Michigan Instruments, Grand Rapids, Michigan, USA) was caliberated and used to measure the ventilatory parameters (PneuView software V3) . Compliance and resistance were adjusted on the simulator for the test conditions.

Four modern critical care ventilators were included in this study, Puritan Bennett 980 (Medtronic, Boulder, Colorado, USA), Infinity V500 (Dräger, Pennsylvania, USA), G5 (Hamilton, Nevada, USA), and the Bellavista 1000e (Vyaire, Illinois, USA). All ventilators were calibrated per manufacturer recommendations. All ventilators passed pre-ventilation checks and the same circuit was used in all the studies and with no leaks identified.

The PB 980 and Infinity V500 both utilize an internal flow sensor with an internal pressure sensor. The G5 and Bellavista 1000 both utilize an external flow and pressure sensor.

Each ventilator was tested with three passive, single compartment modes: 1) compliance (C) of 40 ml/cmH$_2$O, resistance (R) of 10 cmH$_2$O, 2) C of 40 ml/cmH$_2$O, R of 20 cmH$_2$O, 3) C of 20 ml/cmH$_2$O, R of 10 cmH$_2$O.

In each study, two different modes of ventilation were evaluated: Volume controlled (VCV) (tidal volume (V_T) 400 ml, respiratory rate (RR) 20, positive end expiratory pressure (PEEP) 5 cmH$_2$O, inspiratory time (Ti) 0.7 seconds) with a continuous (square) flow wave. To be noted, the G5 and the Bellavista ventilators are set using the Ti or I:E ratio and flow would vary accordingly, the 980 ventilator are set using the peak flow only and variable Ti, while the V500 is set using both a fixed inspiratory flow and fixed Ti. Pressure controlled (PCV) (inspiratory pressure (IP) 15 cmH$_2$O, RR 20, PEEP 5 cmH$_2$O, Ti 0.7 seconds), the rise or slope time was adjusted in each ventilator to achieve a near 90-degree angle and avoid a pressure shoot. In each study we measured peak inspiratory flow in L/s, V_T in mL, peak inspiratory pressure (PIP) in cmH$_2$O, and PEEP in cmH$_2$O. All experiments were done using non heated circuit, Teleflex Medical (Pennsylvania, USA), with no HME or filters added to the circuit.

All values were reported as a mean and standard deviation over an acquisition of 50 breaths with each condition. Statistical analysis was performed using JMP Pro version 16.1 (SAS Institute, Cary, North Carolina, USA). A Kruskal-Wallis test was performed to compare the differences between each ventilator to each other across all conditions and modes and to compare each ventilator to a mathematical model. A post-hoc Dunn's test was used to conduct pairwise comparisons between the ventilators with a P value less than 0.05 considered to be statistically significant. A t-test was used to compare the variables between the ventilators' delivered parameters and those measured from the simulator.

Mathematical model derived from the equation of motion. [11]

Inspiratory flow in PCV

$$(\Delta P/R_{aw})\ e^{t/\tau}$$

Inspiratory pressure in VCV

$$E \times V + R \times \dot{V}$$

ΔP is the pressure applied to the airway above PEEP, t is the elapsed time after initiation of the inspiratory phase, and e is the base of the natural logarithm. E: Elastance in cmH_2O/ml, V: Volume in ml, R: Resistance in cmH_2O, $\dot{V}$: flow in $cmH_2O/L/s$, **τ**: time constant

Results

The results of the study are summarized in Tables 1-4. Figure 2 presents the results of the SIVA mathematical model.
The respiratory measurements reported by the ventilators in the tested conditions are presented in Table 1. For all conditions, there were significant differences between all measured values of inspiratory flow, V_T, PEEP, and PIP ($P < 0.001$). Dunn's post-hoc test (table 2) revealed significant differences in all but 8 parameters in the PIP and PEEP, but none between the flow and volume ($P < 0.001$).
The predicted values from the mathematical model were compared using a paired t-test for each of the values from the mechanical ventilators in all the experiments and all values were significantly significant ($P < 0.001$).

Paired t-tests were performed to identify differences between the ventilator measurements to the lung simulator. Comparisons between each ventilator and lung simulator under volume control ventilation are presented in Table 3. The PB 980 showed significant differences in all tested conditions except PEEP tested at C: 40 ml/cmH_2O – R:10 cmH_2O ($P = 0.34$). The V500 showed significant differences across all conditions. The G5 was significantly different, except for PIP at C: 20 ml/cmH_2O – R: 10 cmH_2O ($P = 0.07$). The Bellavista was significantly different in all tested conditions except for tidal volume at C: 40 ml/cmH_2O – R: 20 cmH_2O ($P = 0.31$).

The same comparisons using PCV are presented in Table 4. The PB 980 was significantly different in all conditions except PEEP tested at C: 40 ml/cmH_2O – R: 20 cmH_2O ($P = 0.12$). The V500 was significantly different except for PIP at C: 40 ml/cmH_2O - R 20 cmH_2O ($P = 0.21$), PIP at C: 20 ml/cmH_2O – R: 10 cmH_2O ($P = 0.34$), and PEEP at C: 20 ml/cmH_2O – R: 10 cmH_2O ($P = 0.11$). The G5 and Bellavista were significantly different across all conditions.

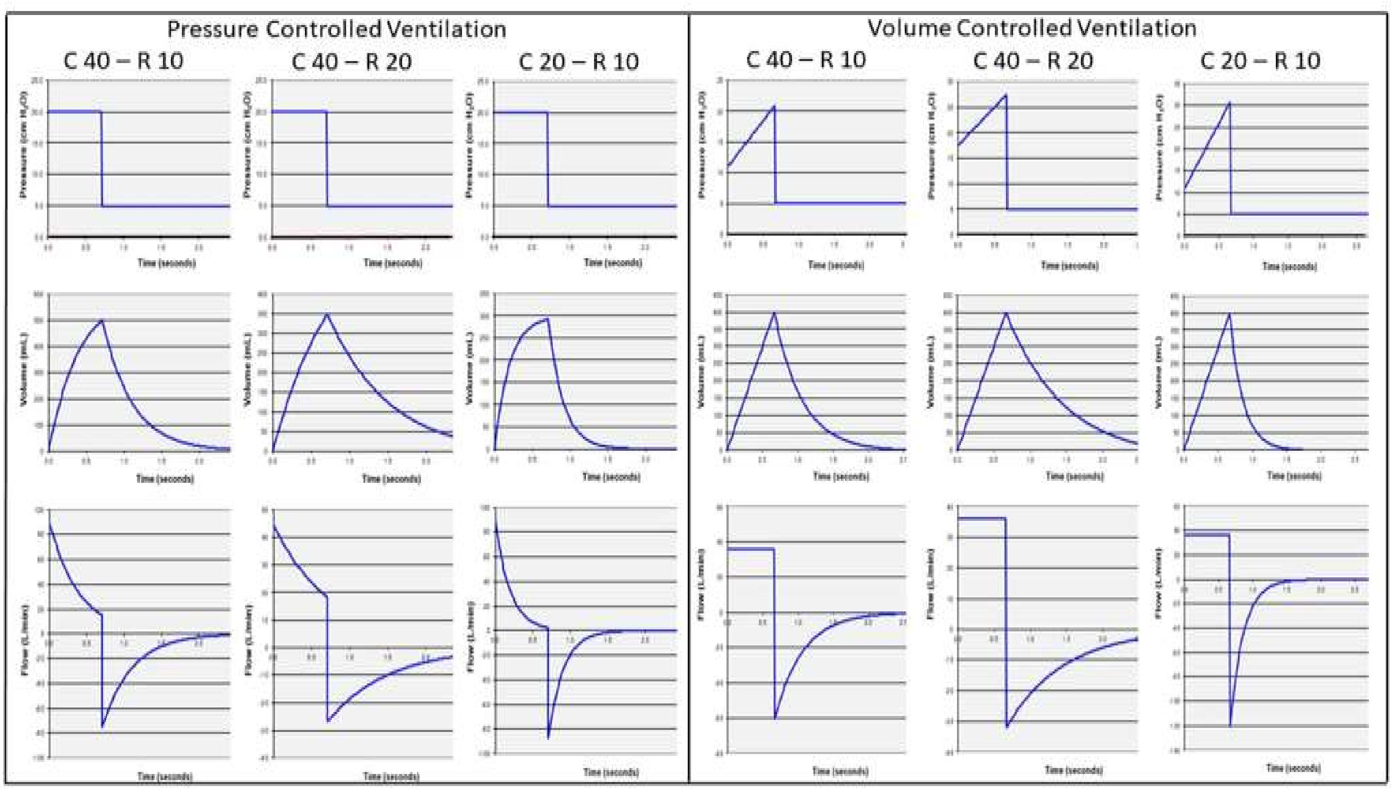

Figure 2: Mathematical model for predicted flow (top), volume (middle), airway pressure (bottom) in volume-controlled ventilation (first 3 columns) and pressure-controlled ventilation (right 3 columns)

Table 1: Kruskal Wallis Test comparing four parameters between the four ventilators. Brackets is the % difference between the measured parameter and the mathematical model. C: static compliance, R: inspiratory resistance, PIF: peak inspiratory flow in L/s, VT: tidal volume in ml, PIP: peak inspiratory pressure in cmH_2O, PEEP: positive end expiratory pressure in cmH_2O.

	Model	PB 980	V 500	G5	Bellavista	P value
	Volume Controlled Ventilation					
C 40 – R10						
PIF	36	40.7 ± 0.1 (13%)	39.5 ± 0.1 (9.7%)	35.9 ± 0.8 (0.2%)	34.8 ± 0.1 (3.3%)	< 0.001
VT	400	381.7 ± 0.9 (4.8%)	389.8 ± 1.5 (2.8)	404.1 ± 4.2 (1%)	395.8 ± 2.9 (1.1%)	< 0.001
PIP	21	21.2 ± 0.02 (0.1%)	21.2 ± 0.1 (0.1%)	20.1 ± 0.4 (4.2%)	19.5 ± 0.06 (7.1%)	< 0.001
PEEP	5	5.3 ± 0.05 (6%)	5.4 ± 0.04 (8%)	5.4 ± 0.03 (8%)	5.1 ± 0.1 (2%)	< 0.001
C 40 – R 20						
PIF	36	40.3 ± 0.1 (11.9%)	39.8 ± 0.1 (10.5%)	35.3 ± 0.1 (1.9%)	34.6 ± 0.1 (3.8%)	< 0.001
VT	400	374.1 ± 0.7 (6.5%)	386.6 ± 1.5 (3.4%)	385.1 ± 0.8 (3.7%)	396.1 ± 3.1 (1%)	< 0.001
PIP	27	28.1 ± 0.02 (4.1%)	28.1 ± 0.1 (4.1%)	24.3 ± 0.1 (10%)	24.5 ± 0.08 (9.2%)	< 0.001
PEEP	5	5.5 ± 0.07 (10%)	5.3 ± 0.05 (6%)	5.3 ± 0.1 (6%)	5.3 ± 0.09 (6%)	< 0.001
C 20 – R 10						
PIF	36	38.9 ± 0.06 (8.1%)	39.4 ± 0.1 (9.4%)	34.1 ± 0.8 (5.2%)	33.1 ± 0.07 (8.1%)	< 0.001
VT	400	369.6 ± 0.3 (7.6%)	379.4 ± 1.4 (5.4%)	383.4 ± 3.7 (4.1%)	375.2 ± 0.5 (6.2)	< 0.001
PIP	31	29.8 ± 0.05 (3.8%)	30.4 ± 0.1 (1.9%)	28.9 ± 0.4 (7%)	28.1 ± 0.06 (9.3%)	< 0.001
PEEP	5	5.4 ± 0.07 (8%)	5.5 ± 0.05 (10%)	5.4 ± 0.07 (8%)	5.2 ± 0.07 (4%)	< 0.001
	Pressure Controlled Ventilation					
C 40 – R10						
PIF	90	44.1 ± 0.14 (51%)	42.6 ± 0.3 (53.7%)	42.7 ± 0.1 (52.5%)	43.1 ± 0.15 (52.1%)	< 0.001
VT	497	447.4 ± 0.8 (9.9%)	422.2 ± 0.7 (15%)	435.7 ± 0.9 (12.3%)	455.3 ± 5.0 (8.4%)	< 0.001
PIP	20	19.6 ± 0.1 (2%)	20.1 ± 0.1 (0.5%)	19.7 ± 0.05 (1.5%)	20.4 ± 0.05 (2%)	< 0.001
PEEP	5	5.3 ± 0.04 (6%)	5.2 ± 0.05 (4%)	5.3 ± 0.06 (5%)	5.1 ± 0.1 (2%)	< 0.001
C 40 – R 20						
PIF	44	34.7 ± 0.1 (21.1%)	32.9 ± 0.1 (25.2%)	33.9 ± 0.13 (24.7%)	32.7 ± 0.3 (25.6%)	< 0.001
VT	344	360.3 ± 0.83 (4.7%)	335.5 ± 0.6 (2.4%)	360.3 ± 0.87 (4.7%)	357.5 ± 2.9 (3.9%)	< 0.001
PIP	20	20.2 ± 0.02 (1%)	19.9 ± 0.1 (0.5%)	20.4 ± 0.05 (2%)	20.5 ± 0.1 (2.5%)	< 0.001
PEEP	5	5.3 ± 0.04 (6%)	5.1 ± 0.04 (2%)	5.2 ± 0.06 (4%)	5.1 ± 0.04 (2%)	< 0.001
C 20 – R 10						
PIF	90	37.6 ± 0.02 (58.2%)	35.6 ± 0.7 (60.4)	36.7 ± 0.31 (59.2%)	36.6 ± 0.09 (59.3%)	< 0.001
VT	292	308.7 ± 0.6 (5.7%)	291.3 ± 1.1 (0.2%)	309.6 ± 1.3 (6%)	313.7 ± 0.7 (7.4%)	< 0.001
PIP	20	20.5 ± 0.1 (2.5%)	20.2 ± 0.1 (1%)	20.9 ± 0.03 (4.5%)	20.9 ± 0.05 (4.5%)	< 0.001
PEEP	5	5.2 ± 0.05 (4%)	5.3 ± 0.05 (6%)	5.3 ± 0.03 (6%)	5.1 ± 0.05 (2%)	< 0.001

Table 2: Post hoc Dunn test showing the non-significant variables.

	Parameter	980	V500	G5	Bellaista	P Value
VCV						
C 40 & R 10	PIP	21.2 ± 0.02	21.2 ± 0.02			0.17
	PEEP	5.4 ± 0.04		5.4 ± 0.03		0.53
C 40 & R 20	PIP	28.1 ± 0.02	28.1 ± 0.02			0.71
	PEEP	5.3 ± 0.05	5.3 ± 0.1			0.38
C 20 & R 10	PEEP	5.4 ± 0.07	5.4 ± 0.07			0.82
PCV						
C 40 & R 10	PEEP	5.3 ± 0.04	5.3 ± 0.04			0.23
C 40 & R 20	PEEP		5.1 ± 0.04		5.1 ± 0.04	0.88
C 20 & R 10	PEEP		5.3 ± 0.05	5.3 ± 0.05		0.69

Table 3: comparison between ventilator – simulator parameters in VCV with T-test and % difference

Volume Controlled Ventilation				
PB 980	**Ventilator**	**Simulator**	**% Difference**	**P value**
C 40 – R10				
PIF	42.6 ± 0.29	40.7 ± 0.1	4.46%	<0.001
VT	407.16 ± 0.52	381.7 ± 0.9	6.25%	<0.001
PIP	21.2 ± 0.02	20.89 ± 0.12	1.48%	<0.001
PEEP	5.3 ± 0.05	5.2 ± 0.05	1.92%	0.34
C 40 – R 20				
PIF	47.13 ± 0.67	40.3 ± 0.1	14.49%	<0.001
VT	457.4 ± 1.11	374.1 ± 0.7	18.21%	<0.001
PIP	37.77 ± 0.09	28.1 ± 0.02	25.6%	<0.001
PEEP	5.5 ± 0.07	5.33 ± 0.02	3.19%	<0.001
C 20 – R 10				
PIF	45.14 ± 0.49	38.9 ± 0.06	13.82%	<0.001
VT	434.13 ± 1.53	369.6 ± 0.3	14.86%	<0.001
PIP	30.12 ± 0.18	29.8 ± 0.05	1.06%	<0.001
PEEP	5.4 ± 0.07	5.33 ± 0.04	1.31%	<0.001
V 500	**Ventilator**	**Simulator**	**% Difference**	**P value**
C 40 – R10				
PIF	42.13 ± 0.13	39.5 ± 0.1	6.24%	<0.001
VT	398.6 ± 2.7	389.8 ± 1.5	2.2%	<0.001
PIP	21.2 ± 0.1	20.38 ± 0.1	4.02%	<0.001
PEEP	5.4 ± 0.04	5.3 ± 0.09	1.88%	<0.001
C 40 – R 20				
PIF	42.38 ± 0.08	39.8 ± 0.1	6.08%	<0.001
VT	399.58 ± 0.6	386.6 ± 1.5	3.25%	<0.001
PIP	28.1 ± 0.1	27.47 ± 0.18	2.29%	<0.001
PEEP	5.3 ± 0.08	5.3 ± 0.05	0.5%	0.04
C 20 – R 10				
PIF	42.43 ± 0.15	39.4 ± 0.1	7.14%	<0.001
VT	399.74 ± 1.07	379.4 ± 1.4	5.09%	<0.001
PIP	30.4 ± 0.1	29.32 ± 0.27	3.68%	<0.001
PEEP	5.5 ± 0.05	5.34 ± 0.08	2.99%	<0.001
G5	**Ventilator**	**Simulator**	**% Difference**	**P value**
C 40 – R10				
PIF	34.9 ± 0.8	33.15 ± 0.37	5.27%	<0.001
VT	402.1 ± 4.2	396.11 ± 0.85	1.51%	<0.001
PIP	20.19 ± 0.2	20.1 ± 0.4	0.44%	0.003
PEEP	5.4 ± 0.03	5.16 ± 0.09	4.65%	<0.001
C 40 – R 20				
PIF	35.3 ± 0.1	33.06 ± 0.34	6.77%	<0.001
VT	386.24 ± 1.54	385.1 ± 0.8	0.29%	0.003
PIP	25.36 ± 0.16	24.3 ± 0.1	4.18%	<0.001
PEEP	5.3 ± 0.1	5.17 ± 0.1	2.51%	<0.001
C 20 – R 10				
PIF	34.1 ± 0.8	32.92 ± 0.39	3.58%	<0.001
VT	392.05 ± 0.84	383.4 ± 3.7	2.21%	<0.001
PIP	29.01 ± 0.23	28.9 ± 0.4	0.38%	0.07
PEEP	5.3 ± 0.07	4.97 ± 0.08	6.22%	<0.001

Bellavista	Ventilator	Simulator	% Difference	P value
C 40 – R10				
PIF	35.01 ± 0.55	34.8 ± 0.1	0.59%	0.013
VT	395.8 ± 2.9	393.47 ± 1.66	0.59%	0.03
PIP	19.5 ± 0.06	18.49 ± 0.12	5.46%	<0.001
PEEP	5.1 ± 0.1	5.08 ± 0.05	0.39%	<0.001
C 40 – R 20				
PIF	35.22 ± 0.6	34.6 ± 0.1	1.76%	0.001
VT	396.1 ± 3.1	394.58 ± 1.55	0.38%	0.31
PIP	24.5 ± 0.08	23.63 ± 0.12	3.68%	<0.001
PEEP	5.3 ± 0.09	5.05 ± 0.06	4.95%	<0.001
C 20 – R 10				
PIF	34.18 ± 0.84	33.1 ± 0.07	3.16%	<0.001
VT	383.5 ± 2.63	375.2 ± 0.5	2.16%	<0.001
PIP	28.1 ± 0.06	26.48 ± 0.18	6.11%	<0.001
PEEP	5.2 ± 0.07	5.05 ± 0.05	2.97%	<0.001

Table 4: comparison between ventilator – simulator parameters in PCV with T-test and % differences.

Pressure Controlled Ventilation				
PB 980	**Ventilator**	**Simulator**	**% Difference**	**P value**
C 40 – R10				
PIF	52.33 ± 0.23	44.07 ± 0.14	15.78%	<0.001
VT	492.37 ± 0.75	447.22 ± 0.78	9.17%	<0.001
PIP	20.29 ± 0.08	19.65 ± 0.02	3.15%	<0.001
PEEP	5.33 ± 0.06	5.28 ± 0.04	0.19%	0.001
C 40 – R 20				
PIF	38.33 ± 0.61	34.72 ± 0.1	9.42%	<0.001
VT	360.44 ± 0.84	353.83 ± 2.23	1.87%	<0.001
PIP	20.4 ± 0.09	20.2 ± 0.02	0.98%	0.003
PEEP	5.32 ± 0.04	5.31 ± 0.02	0.19%	0.12
C 20 – R 10				
PIF	38.33 ± 0.61	37.55 ± 0.11	2.03%	<0.001
VT	319.2 ± 0.61	308.71 ± 0.62	3.29%	<0.001
PIP	20.5 ± 0.05	20.33 ± 0.19	0.84%	0.002
PEEP	5.34 ± 0.03	5.25 ± 0.05	1.69%	<0.001
V 500	**Ventilator**	**Simulator**	**% Difference**	**P value**
C 40 – R10				
PIF	51.73 ± 0.38	42.59 ± 0.1	17.69%	< 0.001
VT	458.36 ± 1.14	421.94 ± 0.72	7.95%	<0.001
PIP	20.03 ± 0.11	20.2 ± 0.05	0.01%	<0.001
PEEP	5.27 ± 0.07	5.14 ± 0.04	2.47%	<0.001
C 40 – R 20				
PIF	37.45 ± 0.16	32.91 ± 0.1	12.12%	<0.001
VT	355.24 ± 0.6	335.1 ± 0.46	5.67%	<0.001
PIP	19.92 ± 0.13	19.89 ± 0.05	0.3%	0.21
PEEP	5.25 ± 0.08	5.12 ± 0.04	2.47%	<0.001
C 20 – R 10				
PIF	46.99 ± 0.55	35.57 ± 0.68	24.3%	<0.001
VT	318.24 ± 1.84	291.19 ± 1.1	8.49%	<0.001
PIP	20.24 ± 0.09	20.21 ± 0.03	0.15%	0.34
PEEP	5.32 ± 0.05	5.26 ± 0.06	1.14%	0.11

G5	Ventilator	Simulator	% Difference	P value
C 40 – R10				
PIF	44.86 ± 0.55	42.66 ± 0.16	4.9%	<0.001
VT	435.6 ± 0.91	430.05 ± 2.63	1.29%	<0.001
PIP	19.91 ± 0.13	19.72 ± 0.06	1.8%	<0.001
PEEP	5.37 ± 0.06	5.16 ± 0.09	4.07%	<0.001
C 40 – R 20				
PIF	35.37 ± 0.38	33.92 ± 0.14	4.09%	<0.001
VT	360.22 ± 0.87	352.86 ± 1.12	0.29%	<0.001
PIP	20.35 ± 0.05	19.99 ± 0.24	4.18%	<0.001
PEEP	5.38 ± 0.06	5.14 ± 0.1	4.07%	<0.001
C 20 – R 10				
PIF	42.73 ± 1.08	39.63 ± 0.31	7.25%	<0.001
VT	313.1 ± 1.02	309.53 ± 1.29	1.14%	<0.001
PIP	20.9 ± 0.03	19.95 ± 0.14	4.76%	<0.001
PEEP	5.39 ± 0.04	4.97 ± 0.07	8.45%	<0.001
Bellavista	**Ventilator**	**Simulator**	**% Difference**	**P value**
C 40 – R10				
PIF	43.46 ± 1.15	43.07 ± 0.15	0.89%	0.02
VT	454.75 ± 2.9	427.4 ± 1.85	6.39%	<0.001
PIP	20.44 ± 0.05	19.25 ± 0.15	6.18%	<0.001
PEEP	5.02 ± 0.1	5.08 ± 0.05	1.18%	0.01
C 40 – R 20				
PIF	32.7 ± 0.31	32.12 ± 1.64	1.81%	<0.001
VT	364.61 ± 1.75	357.28 ± 2.9	2.01%	<0.001
PIP	20.46 ± 0.09	19.45 ± 0.17	5.19%	<0.001
PEEP	5.27 ± 0.04	4.99 ± 0.04	5.61%	<0.001
C 20 – R 10				
PIF	36.58 ± 0.09	35.29 ± 1.10	3.65%	<0.001
VT	313.62 ± 0.67	316.31 ± 1.32	0.01%	<0.001
PIP	20.94 ± 0.05	19.77 ± 0.11	5.92%	<0.001
PEEP	5.26 ± 0.05	5.05 ± 0.05	4.16%	<0.001

Discussion

Variability between the four ventilators

The bench study consisted of utilizing a lung simulator as a comparison for reported ventilator measures in four critical care ventilators. We observed that between all four ventilators, there was a significant difference in nearly all ventilatory parameters for all conditions. These findings support our hypothesis that there are differences in the ventilatory output in the four devices studied.

Our findings are in agreement with many studies that concluded similar results. Yamaguchi and colleagues examined the V_T between three different ventilators using a lung simulator and showed discrepancies in the V_T in the different ventilators and modes.[12] Koyama and colleagues examined the inspiratory pressurization between five ventilators in the PCV mode and found that the pressurization was largely different among the different types of ventilators. [13] Another study by Jammes showed wide variability of the respiratory variables between 5-30%. [14] According to Sandborn, [5] pressure measurements range between 3% and 5% of reading, and flow measurements range between 6% and 10% (3 standard deviations of the mean).

The ventilators included in the study possess a variety of sensor types. The Medtronic PB 980 utilizes a hot film anemometer as a flow sensor and a solid-state differential pressure transducer. The Dräger Infinity V500 also uses hot film anemometry to measure flow and includes a differential pressure sensor. The Hamilton G5 uses a variable orifice flowmeter as well as a differential pressure transducer. The Vyaire Bellavista 1000 also uses a variable orifice flowmeter which is then used to convert flow data to pressure.

The variation seen throughout the tests likely result from the electronic differences in circuitry from the manufacturer's sensor device configuration. The use of hot wire anemometry or variable orifice flowmeters may influence accuracy, although both are deemed reliable in the industry. Orifice flowmeters may experience a lack of accuracy at low flow rates compared to hot wire anemometry.[3] Pressure sensors tend to exhibit less variability amongst types due to their robust construction. [5] Those findings are in corroboration with our observations as there tended to be more variation from flow-related measurements compared to pressure. Correlation may be more apparent at other testing parameters that model a patient with different respiratory mechanics.

It is important to note that the accuracy of the digital numeric and graphical information displayed on the ventilator CPU are dependent on many factors, starting with sensing the signal (sensors), signal transduction and conversion to digital signal, ventilator algorithms for checking, and converting the signal into digital analogue (numbers and waveforms). The accuracy or lack of in any of those steps will alter the accuracy of measurements.[5]
The accuracy of critical care ventilator sensors is governed by the International Organization for Standardization (ISO) chapter 80601-2-12.[15] The subclauses contained outline the acceptable standard error (maximum bias error and maximum linearity error) for V_T: ± (5 +(10% of the set volume) ml and ± (3,0 +(5 % of the set pressure) cmH_2O. The document governs the compulsory reporting of the ventilator's tested accuracy. The four ventilators tested possess an ISO certification. Operational accuracy for volume, flow, and pressure are listed in each ventilators' manual in addition to their respective testing conditions.

Variability between delivered and measured in each ventilator

The results of the comparison between delivered and measured parameters from each ventilator suggest significant variation in most conditions. This observation is in agreement with Govoni and colleagues as they reported differences in delivered volume and pressure parameters compared to the set inputs noted by the ventilator.[1] The percent difference between the lung simulator and ventilator was an overestimation on the part of the ventilator as nearly all measurements delivered were lower than what was indicated by the ventilator.[16] This is to say that it is expected that the delivered values are lower than the ventilator indications, however, the percent difference observed with larger values draws into question its clinical implications. Aside from the type and the location of the sensors, some of the reasons for those discrepancies are that ventilators use proprietary algorithms to compensate for gas compressed in the delivery tubing, and gas temperature and water vapor corrections.[17] The investigation into the discrepancy between measured and actual measurements, such as volume, become increasingly consequential when considering the ventilation of neonates. Yamaguchi and colleagues [12] noted clinically significant differences in V_T delivered when simulating neonatal lung injury. Furthermore, Lyazidi and colleagues[18] reported clinically significant differences in V_T for their bench study despite incorporating compensation algorithms for volume compression in the breathing circuit.

Ventilators with the external flow sensors (G5 and Bellavista 1000) were observed to have a smaller difference, and thus greater accuracy, between measured and delivered values when measuring inspiratory flow and V_T in comparison to the ventilators with internal flow sensors (Infinity V500 and PB 980). However, for measurements of PIP and PEEP, the two internal pressure sensor ventilators (Infinity V500 and PB980) had a statistically greater accuracy compared to the two external pressure sensor ventilators (G5 and Bellavista 1000). Albeit the statistical differences in PIP and PEEP, those differences were too small and may not be clinically significant. [19]

Variability between the ventilators and the mathematical model

The differences between the mathematical model based on the equation of motion and the actual ventilator delivered parameters are expected. One explanation is that the set lung simulator compliance and resistance are not 100% accurate. The mathematical model does not take in account the additional effects of the artificial airway and circuit compliance, resistance, humidifiers, capnometry, nebulizers, and dead space or the effects of gas temperature and humidity on the flow pattern changes in the ventilator circuits. Perhaps the range of differences might be more important. A previous study by our group comparing the airway pressure decay and flow in airway pressure release ventilation (APRV) between a mathematical model to four critical care ventilators similarly showed significant differences between all the ventilators and the mathematical model. [20]

Limitations, our study has some limitations. Though bench simulator studies are a valuable tool for evaluating the performance of mechanical ventilators, the results must be interpreted through the context of numerous factors in its use to evaluate mechanical ventilators. As noted by Chatburn[17] the artificial testing environment, the lack of physiological feedback, and the inter-device variability of the ventilators all play a factor in the validity of measurements. The four mechanical ventilators included may have performance characteristics that, when measured by the bench simulator, have variations that are not directly comparable between them. The passive model here is devoid of feedback responses to the dynamics exhibited by a patient. Moreover, the bench study does not incorporate operator variability and error present in real-word scenarios. In addition, the discrepancies may arise from algorithms involved in signal processing that transduces signals from the patient to graphical and numerical values.

However, we used the same simulator for all studies so the effect on the results is equal. Additionally, lung simulators use a single compartment model with fixed respiratory mechanics that act differently from real patients' lungs with multi compartmental nonlinear respiratory mechanics. The simulator used in the study also uses sensors for flow, pressures and algorithms that translates the variables into graphical and numerical values which can have their own errors. However, we used the same simulator for all the experiments so the effect on the results is equal.

Statistics:
It is important to note that statistical significance does not necessarily equate to clinical significance. Some results may be statistically significant, but the magnitude of the effect may be small and not meaningful in clinical terms or its impact on patient outcomes. In our study, the PIP and PEEP were significantly different, however the magnitude of differences were very small, making them likely to be clinically insignificant.

Conclusion

In this study, we found that all four ventilators were different from one another in measuring the V_T , inspiratory flow, PIP, and PEEP. Ventilators with flow sensors distal (internal) to the patient showed better accuracy in measuring pressures. On the other hand, ventilators with proximal flow sensors had better accuracy in measuring inspiratory flow and volume. Clinicians should be aware that different devices may yield different results for set paraments. Given the multitude of factors involved in measurements, data transduction and processing, we could not make an overall conclusion on superiority of sensor placement for ventilatory measurement accuracy.

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