Accuracy of tidal volume delivery by five different models of large-animal ventilators

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OBJECTIVE

To determine the accuracy of tidal volume (V_T) delivery among 5 different models of large-animal ventilators when tested at various settings for V_T delivery, peak inspiratory flow (PIF) rate, and fresh gas flow (FGF) rate.

SAMPLE

4 different models of pneumatically powered ventilators and 1 electrically powered piston-driven ventilator.

PROCEDURES

After a leak flow check, each ventilator was tested 10 times for each experimental setting combination of 5 levels of preset V_T, 3 PIF rates, and 4 FGF rates. A thermal mass flow and volume meter was used as the gold-standard method to measure delivered V_T. In addition, circuit systems of rubber versus polyvinyl chloride breathing hoses were evaluated with the piston-driven ventilator. Differences between preset and delivered V_T (volume error [ΔV_T]) were calculated as a percentage of preset V_T, and ANOVA was used to compare results across devices. Pearson correlation coefficient analyses and the coefficient of determination (r^2) were used to assess potential associations between the ΔV_T and the preset V_T, PIF rate, and FGF rate.

RESULTS

For each combination of experimental settings, ventilators had ΔV_T values that ranged from 1.2% to 22.2%. Mean ± SD ΔV_T was 4.8 ± 2.5% for the piston-driven ventilator, compared with 6.6 ± 3.2%, 10.6 ± 2.9%, 13.8 ± 2.97%, and 15.2 ± 2.6% for the 4 pneumatic ventilators. The ΔV_T increased with higher PIF rates ($r^2 = 0.69$), decreased with higher FGF rates ($r^2 = 0.62$), and decreased with higher preset V_T ($r^2 = 0.58$).

CONCLUSIONS AND CLINICAL RELEVANCE

Results indicated that the tested ventilators all had ΔV_T but that the extent of each of ΔV_T varied among ventilators. Close monitoring of delivered V_T with external flow and volume meters is warranted, particularly when pneumatic ventilators are used or when very precise V_T delivery is required.
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Respiratory depression is a common complication in animals undergoing general anesthesia and is a particular concern in horses because atelectasis formation in their dependent lungs may lead to development of hypercapnia, hypoxemia, and acid-base imbalances.[1] Although mechanical ventilation is commonly used to prevent or treat lung collapse and related pulmonary gas exchange disturbances in large animals, it may also cause various complications, particularly when the ventilator setting is incorrect, the device malfunctions, or the V_T delivery is inaccurate. To avoid hypo- or hyperventilation and potentially associated ventilation-induced lung injury, it is critical to deliver an adequate and accurate V_T to a patient.[2,3] Even during volume-control ventilation, the V_T that actually reaches a patient's lungs might become smaller than the volume set on a ventilator for various reasons, including losses by compliance of the breathing system and hoses, leaks in the breathing system or around a cuffed endotracheal tube, and gas compression.[4,5] Gas compression might be of greater importance in large animals, compared with small animals, because higher peak inspiratory pressures are achieved in breathing circuits during anesthesia of large animals. In addition, the V_T actually delivered might become higher than the preset V_T, such as when high FGF rates are used.[4]

In piston-driven ventilators, the area of the piston is fixed. Thus, the volume of gas delivered by the piston is directly related to the linear movement of the piston in the piston chamber, and the V_T delivery should be most accurate. A recent study[5] revealed

ABBREVIATIONS

ΔV_T	Volume error (difference between preset and actually delivered tidal volume)
FGF	Fresh gas flow
PIF	Peak inspiratory flow
PVC	Polyvinyl chloride
RR	Ventilation rate
T_{exp}	Expiratory time
T_{insp}	Inspiratory time
TMFVM	Thermal mass flow and volume meter
V_T	Tidal volume

that an electrically powered and microprocessor-controlled piston ventilator for use in large-animal veterinary medicine delivers a V_T with a ΔV_T of only 5% above or below the equipment preset V_T and that a calibration factor could be determined to further increase accuracy.[5] In contrast, most pneumatically powered ventilators for use in large animals appear to be less accurate, despite the possibility of semiquantitatively estimating the V_T by observing movement of the bellows in a transparent cylinder housing marked with a graduated scale in liters. Therefore, pneumatic ventilators may require closer monitoring of the truly delivered V_T.[6]

To our knowledge there has not been a systematic evaluation of the accuracy of V_T delivery with commonly used pneumatic, large-animal ventilators. Therefore, the goal of the study reported here was to determine the accuracy of V_T delivery among 5 different models of large-animal ventilators (4 pneumatically driven ventilators and 1 electrically driven piston ventilator) when tested at various settings for V_T delivery, PIF rate, and FGF rate. We hypothesized that, because of their design, pneumatic ventilators would be less accurate in delivering a desired (ie, preset or dialed) V_T than would the piston ventilator and that the magnitude of ΔV_T would be affected by the PIF and FGF rates, preset V_T, and compliance of the breathing hoses used in the anesthetic circuit system.

Materials and Methods

Included in the study were 5 different models of ventilators frequently used in clinical practice for anesthesia of large animals at the New Bolton Center of the University of Pennsylvania's School of Veterinary Medicine and at the Rood and Riddle Equine Hospital in Lexington, Ky. The anesthesia ventilators tested included 4 pneumatically driven ventilators equipped with bellows (ventilators A through D) and 1 electrical motor–driven piston ventilator (ventilator E).

Ventilator A[a] was classified as a dual-circuit, time-cycled, pneumatically powered, and electronically controlled ventilator. The ventilator operated with hanging (descending) bellows suspended in a plexiglass cylinder marked with a graduated scale in liters (range, 0.5 to 15 L). The V_T was set by manually adjusting the maximum descent of the bellows and, hence, their filling volume, thereby allowing for volume-targeted ventilation. To do so, an anesthetist turned a crank that was at the front and bottom of the bellows housing. This set a stamp in motion within the bellows chamber so that the bellows would fill only to the desired V_T (range, 0.5 to 15 L). The control unit was equipped with an on-off switch, PIF rate regulator, RR dial (range, 1 to 99 breaths/min), and inspiratory-to-expiratory ratio dial (range, 1:1 to 1:4.5).

Ventilator B[b] was also a dual-circuit, time-cycled, pneumatically powered, and electronically controlled respirator, designed with hanging bellows. Somewhat similar to ventilator A, the anesthetist could rotate a crank on the side of the control unit that set in motion a wire rope that was fixed to a metal plate at the bottom of the bellows. By shortening this wire rope, the maximum descent of the bellows and thus their filling volume were adjusted to a desired volume between 0.5 and 15 L, thereby allowing for volume-targeted ventilation. The control dials included an on-off switch and allowed for adjustments to the RR, T_{insp}, and PIF rate. The V_T was controlled by adjusting the PIF rate and T_{insp} until the desired V_T (range, 0.5 to 15 L) was obtained. The V_T was estimated by visualizing the movement of the bellows in their cylinder housing (graduated in liters), thereby allowing for volume-targeted ventilation.

Ventilator C[c] was a pneumatically powered, time-cycled, and electronically (microprocessor) controlled dual-circuit ventilator with standing (ascending) bellows. The control dials allowed adjustment to the PIF rate (range, 10 to 600 L/min), T_{insp}, and RR (range, 2 to 15 breaths/min). In addition, the control unit included a power switch and a manual ventilation button. By adjusting the PIF rate and T_{insp}, the operator could preset the desired V_T, which was estimated by visualizing the movement of the bellows in their cylinder housing (graduated in liters), thereby allowing for volume-targeted ventilation. The inspiratory-to-expiratory ratio, calculated by the microprocessor and based on the selected T_{insp} and RR, was digitally displayed.

Ventilator D[d] was a dual-circuit, time-cycled, and solely pneumatically powered ventilator that was without any electronic controls and free of any ferrous metals. This ventilator was MRI compatible, and adjustable settings included only the on-off knob; PIF rate, T_{insp}, and T_{exp} knobs; and a manual ventilation button. By adjusting the PIF rate (range, 10 to 600 L/min) and T_{insp}, the operator preset the desired V_T, which was, as with the aforementioned ventilators, estimated by visualizing the movement of the bellows in their cylinder housing (graduated in liters) and thereby allowed for volume-targeted ventilation. By adjusting the T_{insp} and T_{exp}, an operator set the RR.

Ventilator E[e] was an anesthesia unit equipped with a single-circuit, piston ventilator and was volume cycled. Instead of the bellows or rebreathing bag used in pneumatic ventilators, ventilator E had a stainless steel piston with 2 rolling diaphragms housed in a stainless steel cylinder. The control dials of ventilator E allowed setting the V_T (range, 0.1 to 20 L), RR (range, 1 to 20 breaths/min), T_{insp} (range, 0.5 to 4.0 seconds), maximum work pressure limit (range, 10 to 80 cm H_2O), continuous positive airway pressure or positive end-expiratory pressure (range, 0 to 50 cm H_2O, in 1-cm H_2O increments), and trigger sensitivity (when the ventilator was operated in the assisted ventilation mode). The ventilator's microprocessor automatically determined the T_{exp} and PIF rate on the basis of these preset parameters.[7] Ventilator E was tested with 2 different circuit configurations, one with elastic black rubber breathing hoses and the other with largely noncompliant, transparent PVC breathing hoses, to assess the impact of breathing circuit compliance on the accuracy of V_T delivery.

None of the tested ventilators compensated for variable compliance of its anesthetic circuit system setup, and none was equipped with a fresh gas–decoupling valve. In modern anesthetic systems made for use in humans, a fresh gas–decoupling valve is positioned between the fresh gas source and the ventilator and, during patient inspiratory phase, diverts the FGF to a reservoir bag, thereby eliminating any impact by FGF rate on the delivered V_T.[6-10]

Experimental design

For each anesthetic ventilator, a gas leak check of the anesthetic circuit system setup was performed before experimenting with the ventilator. For the gas leak check, the Y-piece of the anesthetic circuit was closed with a rubber plug, the adjustable pressure relief valve of the anesthesia circuit was closed, and the circuit was pressurized with 100% O_2. The leak was considered acceptable if an FGF rate < 500 mL/min was needed to maintain a constant pressure of 20 cm H_2O. After results of a gas leak check were acceptable, the rubber plug was removed from the Y-piece of the anesthetic circuit, and a TMFVM,[f] with an 8-L calibration syringe[g] attached, was connected to the Y-piece as previously described.[5] The recently validated[5] TMFVM was used as the gold-standard method to measure the delivered V_T. The calibration syringe was ventilated at 5 levels of V_T (1.0, 2.5, 4.0, 5.5, and 7.0 L), each with 3 different preset PIF rates (approx 100, 150, and 200 L/min). In addition, for each ventilator, each V_T and PIF setting combination was performed at 4 different FGF rates of 100% O_2: 3, 5, and 7 L/min and the leak flow rate for the given anesthetic ventilator setup. After each V_T delivery, the syringe plunger was manually pushed back to empty the syringe. Each test was performed at room temperature and dry gas conditions. Each V_T administration was repeated 10 times, and the delivered V_T was measured with a TMFVM, then recorded. All manually logged data were entered into spreadsheets[h] for subsequent statistical analysis.

Statistical analysis

All data recorded were tested for normal distribution with the Shapiro-Wilk test and visual analysis of Q-Q plots. For each experimental setting, the mean ± SD was calculated for all 10 repetitive measurements of delivered V_T. With those means for each tested ventilator and experimental setting combination, the mean ΔV_T was calculated as a percentage of the preset V_T for each combination. Next, for each ventilator, the complete set of mean ΔV_T data recorded under the various experimental setting combinations was pooled, and ANOVA, with α set to 5% and values of $P < 0.05$ considered significant, was used to compare results across ventilators to determine which ventilators performed the best with respect to having had the lowest pooled mean ΔV_T. Any relationship detected between the ΔV_T and combinations of preset $V_{T,}$ PIF rate, and FGF rate was analyzed by determining the Pearson correlation coefficient and the coefficient of determination (r^2), with the α set to 5% and values of $P < 0.05$ considered significant. Data analysis was performed with available software.[h,i]

Results

Overall, the leak rate for anesthetic ventilator setups was similar, with a mean ± SD leak rate of 0.261 ± 0.04 L O_2/min. Therefore, an FGF rate of 0.25 L O_2/min was used as the leak rate when testing each ventilator setup at the various PIF rate and V_T settings.

For each ventilator and each experimental setting combination tested, the mean ± SD delivered V_T was calculated on the basis of results from 10 repetitive measurements. All results for delivered V_T were smaller than the preset V_T. Because all results for SD of the mean delivered V_T were ≤ 0.75% of the mean V_T, only the mean delivered V_T results were used for further data analysis. With the mean delivered V_T for each ventilator and experimental setting combination, the difference between the preset (dialed) V_T and the mean delivered V_T was calculated as a percentage of the preset V_T to yield the respective mean ΔV_T **(Table 1)**. Overall, the mean ΔV_T ranged from 1.2% (ventilator E, with a PIF rate of 200 L O_2/min, FGF rate of 3 L O_2 /min, and use of transparent PVC breathing hoses) to 22.2% (ventilator D, with a PIF rate of 200 L O_2/min, FGF rate of 0.25 L O_2/min, and use of transparent PVC breathing hoses).

For each ventilator, the complete set of the mean ΔV_T data recorded under the various experimental settings was pooled, then ANOVA was used to compare results across ventilators **(Table 2)**. Ventilator E (an electrically powered and microprocessor-controlled piston ventilator[e]), when used with an anesthetic breathing circuit of transparent PVC breathing hoses (like those used during testing of all the pneumatically powered ventilators[a-d]), was the most accurately operating ventilator in that it had the lowest pooled mean ΔV_T (4.8 ± 2.5%). In addition, the pooled mean ΔV_T was significantly ($P < 0.001$) lower (better) for ventilators A (6.6 ± 3.2%) and B (10.6 ± 2.9%) that had hanging bellows, compared with ventilators C (13.8 ± 3.0%) and D (15.2 ± 2.6%) that had standing bellows and consistently produced the largest mean ΔV_T values. Of note, the mean ΔV_T values were similar for ventilator A and ventilator E tested with PVC breathing hoses as long as the preset V_T was ≤ 4 L and the PIF rate was ≤ 100 L O_2/min. For ventilator E, the mean ΔV_T was consistently larger when operated with breathing hoses made of more elastic black rubber material (6.4 ± 3.4%), compared with less elastic PVC breathing hoses (4.8 ± 2.5%), but ventilator E still performed overall with greater accuracy than any of the pneumatic ventilators (A through D).

Table 1—Summary of the mean ΔV_T (as a percentage of the preset V_T) calculated from results of 10 repetitive measurements for each combination of experimental settings (V_T [1.0, 2.5, 4.0, 5.5, and 7.0 L O_2], PIF rate [approx 100, 150, and 200 L O_2/min], and FGF rate [0.25 {leak rate}, 3, 5, and 7 L O_2/min]) in each of 5 different models of large-animal ventilators (4 pneumatic [ventilators A and B with hanging bellows and ventilators C and D with standing bellows] and 1 piston-driven [ventilator E]).

			Ventilators*					
							E	
PIF rate (L O_2 /min)	FGF rate (L O_2 /min)	V_T (L O_2)	A	B	C	D	BR	PVC
100	0.25†	1.0	5.3	12.5	15.6	20.9	11.0	8.5
		2.5	5.1	10.2	14.2	18.5	7.2	5.3
		4.0	4.5	9.5	13.5	17.2	5.3	4.7
		5.5	3.4	9.1	13.6	17.5	4.7	4.2
		7.0	2.8	8.7	12.1	16.3	3.1	3.5
	3	1.0	4.8	10.4	13.6	17.3	8.9	7.4
		2.5	4.3	9.4	12.5	15.5	7.3	4.8
		4.0	4.6	9.5	11.9	13.2	4.9	4.1
		5.5	5	8.3	11.4	13.4	5.5	3.4
		7.0	3.2	7.6	12	11.2	4.3	3.1
	5	1.0	3.2	9.4	11.6	15.8	4.9	5.6
		2.5	3.9	8.1	10.2	14.2	4.6	3.2
		4.0	3.4	7.1	9.9	13.3	3.3	3.6
		5.5	2.4	6.5	8.7	11.9	3.9	2.7
		7.0	2.8	6.1	8.9	10.2	3.4	2.2
	7	1.0	3.6	8.6	10.1	14.5	4.5	3.5
		2.5	3.3	5.5	9.2	13.2	3.1	2.1
		4.0	3.7	6.2	9.3	12.9	2.7	1.9
		5.5	3.1	4.9	8.4	11.4	2.2	2.1
		7.0	2.7	4.7	9.2	9.3	1.5	1.8
150	0.25†	1.0	6.5	14.3	18.6	18.7	14.2	11.0
		2.5	6.5	13.1	17.2	16.8	7.2	7.2
		4.0	6.1	12.5	17.1	15.3	6.2	5.9
		5.5	6.2	11.1	16.4	14.2	5.5	4.7
		7.0	5.4	9.8	14.8	12.9	6.5	4.2
	3	1.0	7.6	13	17.5	19.4	12.2	9.1
		2.5	7.2	11.4	15.9	17.2	6.7	4.3
		4.0	7.6	10.8	14.3	16.3	4.6	3.2
		5.5	6.8	9.3	13.9	14.9	4.4	3.6
		7.0	6.2	8.1	13.1	12.1	4.5	2.2
	5	1.0	6.2	11.9	15.4	17.5	10.9	7.6
		2.5	5.8	10.6	15.3	14.6	7.3	4.9
		4.0	5.7	9.4	14.1	15.2	6.4	3.3
		5.5	5.7	9.6	13.6	13.2	5.8	3.7
		7.0	5.3	9.5	11.8	11.7	3.4	2.4
	7	1.0	4.4	11.2	13.4	18.2	10.8	8.0
		2.5	4.1	9.3	12.3	16.4	6.4	5.4
		4.0	3.8	10.3	11.9	13.0	5.5	3.8
		5.5	3.3	8.4	11.2	12.4	3.9	2.3
		7.0	3.1	7.6	12.1	9.8	2.3	1.2
200	0.25†	1.0	15.2	17.8	19.8	22.2	16.7	13.5
		2.5	13.6	15.3	17.9	18.7	9.2	6.7
		4.0	13.1	14.6	18.1	17.2	5.2	4.4
		5.5	12.4	12.3	16.8	16.4	4.5	4.9
		7.0	11.5	10.2	16.3	14.9	4.7	3.9
	3	1.0	13.2	16.2	17.2	18.9	16.4	8.3
		2.5	11.5	14.9	16.1	17.1	8.3	6.4
		4.0	10.8	15.1	15.3	16.5	5.4	3.9
		5.5	9.3	13.5	14.1	15.5	5.9	3.3
		7.0	9.4	12.6	13.5	14.8	4.1	2.1
	5	1.0	10.6	14.4	15.9	17.5	13.4	11.0
		2.5	10.2	13.2	14.3	15.4	8.6	5.9
		4.0	9.3	13.6	14.6	16.3	4.4	3.9
		5.5	8.8	11.9	13.7	14.7	5.6	4.1
		7.0	8.4	12.1	13.1	13.9	3.7	2.8
	7	1.0	9.3	13.4	16.2	16.9	12.3	7.4
		2.5	8.6	11.3	15.2	15.5	7.6	5.9
		4.0	8.7	10.5	13.8	14.3	5.4	3.3
		5.5	8.2	9.4	14.1	14.8	6.9	3.7
		7.0	7.7	8.9	11.5	13.2	6.5	4.1

*Values reported as the mean ΔV_T, each as a percentage of the respective preset V_T. †Leak rate for all tested ventilator circuit setups was similar, with a mean leak rate of 0.261 ± 0.04 L O_2/min.

BR = Black rubber breathing hoses used. PVC = Transparent PVC breathing hoses used.

Table 2—Results of ANOVA to identify differences in pooled mean ΔV_T values among the ventilators described in Table 1.

				E	
Ventilator	**B**	**C**	**D**	**BR**	**PVC**
A	3.94 ± 0.56*	7.11 ± 0.54*	8.56 ± 0.58*	–0.21 ± 0.61	–1.88 ± 0.52*
B	—	3.17 ± 0.51*	4.63 ± 0.51*	–4.15% ± 0.57*	–5.83 ± 0.49*
C	—	—	1.45 ± 0.49*	–7.32 ± 0.56*	–9.01 ± 0.48*
D	—	—	—	–8.77 ± 0.55*	–10.45 ± 0.47*
E (BR)	—	—	—	—	–1.67 ± 0.54*

Values reported as the differences in means ± SDs of the pooled ΔV_T for each row and column pairwise comparison between ventilators. Negative values indicated that the ventilator listed at the top of the column had a lower (better) V_T than did the ventilator listed at the far left of the row.

*The pooled mean ΔV_T differed significantly ($P < 0.005$) between the ventilator listed at the top of the column and the ventilator listed at the far left of the row.

See Table 1 for remainder of the key.

The ΔV_T significantly correlated with the rates of PIF ($r^2 = 0.69$; $P = 0.003$) and FGF ($r^2 = 0.62$; $P < 0.001$). With all ventilators tested, an increase in the PIF rate resulted in a decrease in the delivered V_T and hence an increase in the ΔV_T. In contrast, with an increase in the FGF rate, the delivered V_T increased and, thus, the ΔV_T decreased. Furthermore, the preset V_T correlated significantly ($r^2 = 0.58$; $P < 0.001$) with the ΔV_T in that an increase in the V_T resulted in a decrease of the ΔV_T.

Discussion

Results of the present study confirmed our hypothesis that pneumatically powered ventilators would be less accurate in delivering a desired (ie, preset or dialed) V_T than would electrical motor-driven piston ventilators and that the magnitude of the ΔV_T would be affected by the PIF and FGF rates, preset V_T, and compliance of the breathing hoses used in the anesthetic circuit system. These results also corroborated findings from a study[8] of anesthesia ventilators widely used in human medicine that shows the smallest ΔV_T with a piston-driven ventilator.

Unless a ventilator unit is equipped with a fresh gas–decoupling valve, fresh gas will flow continuously throughout the respiratory cycle and therefore increase the V_T delivered by the ventilator.[9] A higher FGF rate and longer T_{insp} will result in a larger ΔV_T. To prevent such an additive impact on the delivered V_T by the FGF rate, contemporary anesthesia ventilators used in human medicine have been equipped with a fresh gas–decoupling mechanism.[6-10] The impact of the FGF rate on V_T delivery is most critical in patients requiring ventilation with small V_T or periods of high-flow anesthesia.

Because the ventilators tested in the present study each lacked a fresh gas–decoupling mechanism, one would expect an increase in delivered V_T when the FGF was increased. Additionally, the finding that every ventilator in the present study had delivered V_T less than the preset V_T at all experimental setting combinations suggested that the FGF rate compensated only to some extent for the device-specific ΔV_T and, thus, artificially reduced the ΔV_T under test conditions with higher FGF rates. Although not observed in our study, this effect in very precisely operating ventilators could potentially lead to hyperventilation and alveolar overinflation if patients are small or suffer from parenchymal lung disease that would require ventilation with small V_T.[1]

The compliance of the breathing circuit has been recognized to have a marked impact on V_T delivery.[11] Every anesthetic breathing circuit has its own specific compliance that is determined by the stretchiness of its elastic components, such as bellows (or bags in older models of pneumatic ventilators) and breathing hoses.[11] A previous study[12] shows that the magnitude of volume losses and the efficiency of an anesthetic circuit are dependent on the material of the breathing system components. Similarly, our results indicated that the mean pooled ΔV_T for ventilator E was larger when tested with the more compliant rubber breathing hoses, compared with the less compliant PVC breathing hoses. This observed difference in the ΔV_T on the basis of the type of breathing hoses used could have underestimated what would be commonly encountered under clinical conditions in large animals. Ideally, to measure compliance losses properly, the experimental setup should have mimicked an airway pressure of 20 to 30 cm H_2O that is usually observed during mechanical ventilation in horses.

In addition, the engineering design of ventilators determines their magnitude of ΔV_T,[13] and we confirmed this notion. The ΔV_T was the smallest for ventilator E (a piston [noncompliant steel] ventilator) when PVC breathing hoses were used, whereas ventilators A through D (rubber bellows–equipped, pneumatically powered ventilators) connected to the PVC breathing hoses all produced a ΔV_T that was substantially larger than that produced by ventilator E. In pneumatically powered ventilators, movement of the bellows is controlled by the driving gas that enters the bellows chamber, pushes the bellows upwards in ventilators with hanging bellows[a,b] or downwards in ventilators with standing bellows,[c,d] and thereby displaces a volume of breathing gas into the breathing circuit equal to the volume of driving gas that entered the bellows chamber.[13] However, the pressure that builds in the breathing circuit because of the bellows movement and constitutes the driving force for delivery of the V_T to the patient (to the calibration syringe in our study) is determined by the resistance and compliance of the breathing circuit components, including the bellows themselves.[13] The more compliant those components are, the lower the pressure is within the breathing circuit and, consequently, the less compressed the gas is in the bellows chamber, all leading to a lower delivered V_T. Variable compression of the driving gas is a fundamental obstacle to accurate V_T delivery by any pneumatically powered, bellows-type ventilator.[13] To reduce compliance-related ΔV_T, some microprocessor-controlled ventilators perform an automated compliance test and then compensate for any compliance-related loss of delivered V_T by deviating from the preset V_T, which eventually allows for greater precision of V_T delivery.[1,5,8]

Our findings further suggested that design differences in the bellows configuration accounted for differences in the ΔV_T because both ventilators that operated with hanging bellows (ventilators A and B) produced a substantially smaller ΔV_T than the 2 units with standing bellows (ventilators C and D). Furthermore, even in the case of the same type of bellows (eg, hanging bellows), differences in bellowed-ventilator designs will influence the accuracy of volume delivery. For instance, ventilator A was filled, as the manufacturer claimed,[13] only to the desired V_T that was preset by the operator who manually adjusted a plunger within the hanging bellows cylinder that limited the descent of the bellows. Provided the operator set a sufficient PIF rate and T_{insp}, this mechanism would then ensure that the bellows emptied completely with each inspiration of the patient. This also explains why the impact of the bellows compliance was less in ventilator A (hanging bellows), compared with ventilators C and D (standing bellows), as long as the bellows were stretched less (as with smaller preset V_T settings) and lower PIF rates ($\leq$ 100 L/min) were applied, and why the ΔV_T (under our testing conditions) was smaller for ventilator A, compared with ventilators C and D. Furthermore, if a ventilator with bellows begins the inspiratory phase with the bellows at maximum volume, as occurred with ventilators C and D, then compliance of the bellows is also at its maximum, and this alone compromises accurate V_T delivery.

Another cause for a ΔV_T might be a leak in the rebreathing circuit system. Because of the linearity between flow and pressure in a closed system,[14] a higher inspiratory flow would result in a higher system pressure. The leak test was performed with a standard method of only 20 cm H_2O pressure application on the basis of current recommendations.[7,15,16] A higher test pressure during the PIF rate testing could have resulted in a different total leakage. Repeating the leak tests at various pressures could have allowed better estimation of losses in V_T delivery when working with lower or higher peak inspiratory pressures. Consistent with a previous study,[17] findings in the present study indicated that the ΔV_T decreased when larger V_T presets were used. Also, the volume of gas lost by expansion of the anesthetic circuit system during the inspiratory phase produces a ΔV_T that is fixed and therefore relatively higher when small V_T presets are used.[12–18]

There are a number of limitations to the present study that need to be considered when drawing conclusions for clinical settings. First, we did not measure the pressure in the circuit system during testing. It has been shown that volume losses and hence accuracy of V_T delivery by ventilators are correlated with the maximum pressure achieved in the breathing system during inspiration.[12] The questions of whether and to what extent peak anesthetic circuit system pressures exceeded 20 cm H_2O in our study under the different testing conditions cannot be answered. Consequently, we do not know whether higher circuit system pressures could have accounted for volume losses and impacted the ΔV_T during ventilation. Second, V_T delivery by the ventilators was tested at room temperature and dry gas conditions. However, in clinical situations, when a delivered V_T reaches a patient's lungs, the gas becomes saturated with water vapor and becomes warmer. On the basis of physical gas laws, when gases warm, their volumes increase.[17] Likewise, any temperature increase promotes greater elasticity of components of the circuit system, particularly rubber bellows and potentially the breathing hoses, and results in greater compliance of the anesthetic circuit system. Whether these changes are clinically relevant can be answered only in follow-up studies performed with live animals under conditions similar to clinical situations. Third, although a variety of gases, including O_2, N_2, N_2O, He, and medical air (21% O_2 and 79% N_2), are used in large-animal veterinary medicine and particularly in anesthesia of horses, O_2 was the only gas used in the present study. These gases differ in their physical properties, such as viscosity, density, and heat capacity, and accordingly differ in their gas flow patterns.[19,20] A recent study[5] shows that a piston-driven ventilator delivers V_T accurately and independently of the gas mixture used. In contrast to bellows-driven ventilators (defined as dual-circuit ventilators), piston-driven ventilators operate with a single circuit and work basically like a plunger within a syringe that is driven by a microprocessor-controlled electric motor. This unique design allows for very precise V_T delivery because it does not involve an elastic bellows and because it uses a piston instead of a compressible gas to deliver the preset V_T. Further studies are needed to evaluate the accuracy of bellows-driven ventilators when different gas mixtures are used. Fourth, the routine leak test that was performed with each pneumatically powered anesthesia ventilator at the beginning of each experiment did not test the bellows housing for the presence of any gas leak, which, depending on magnitude, could have affected the driving gas flow rate and pressure and thus the delivered V_T. Fifth, for the present study, we used a calibration syringe with a graduated scale up to only 7 L. This limited the maximum V_T we could test. From a statistical perspective and for a better extrapolation of our findings to clinical situations, it would have been valuable to have also tested larger volumes.

Another limitation, common to all bench-type studies, was the difficulty to extrapolate results from the laboratory to in vivo and then to clinical situations in which lung compliance and airway resistance also affect accuracy of V_T delivery. For a given preset V_T, the pressure that results in the breathing circuit is determined by the resistance and compliance of the breathing circuit and the patient's lungs. This applies much more so with pneumatic ventilators with bellows.[13] Because the pressure in the bellows compartment will vary between patients and can vary between breaths in a patient, the gas driving the bellows will be subject to varying degrees of compression that cannot be predicted. Variable compression of the driving gas is a fundamental obstacle to accurate V_T delivery by bellows ventilators. This is particularly true for small V_T deliveries and high inspiratory pressures, the latter of which often occur in horses undergoing colic surgery in dorsal recumbency. The observed inaccuracies in actual V_T delivery and the potential complications associated with inadequate V_T delivery call for routine V_T monitoring in clinical practice. A Pitot tube–based flow sensor is currently the only validated method for accurately measuring inspired and expired V_T in anesthetized horses.[21] Volume-controlled ventilation should ideally be adjusted on the basis of expired V_T.[1,21]

All tested large-animal ventilators tested in the present study had a smaller delivered V_T than preset V_T, and at times the ΔV_T exceeded 10%, which in human medicine is considered the upper limit of what is clinically acceptable.[11] Still, the piston-driven ventilator (ventilator E) performed in this regard substantially better than the pneumatically powered ventilators (ventilators A through D). Ventilator E repetitively surpassed the 10% threshold for ΔV_T only when black rubber breathing hoses and a preset V_T of 1 L were used. Among the pneumatic ventilators, those with hanging bellows (ventilators A and B) performed superior to those with standing bellows (ventilators C and D), with the latter performing consistently with a ΔV_T in excess of 10%, even when tested at larger V_T settings. In all tested ventilators, the ΔV_T depended on settings for V_T and for PIF and FGF rates. Therefore, close monitoring of V_T with external flow and volume meters is warranted, particularly when pneumatic ventilators are used or when very precise V_T delivery is required.

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Footnotes

a. Large Animal Control Center with AVE respirator, serial No. 291, Dräger Inc, Telford, Pa.
b. Surgivet LDS 3000 large animal anesthesia machine with DHV 1000 large animal ventilator, Smiths Medical, Minneapolis, Minn.
c. Model 2800 large animal anesthesia ventilation system, Mallard Medical, Redding, Calif.
d. Model 2800C large animal anesthesia ventilation system, Mallard Medical, Redding, Calif.
e. Tafonius Junior, Hallowell Engineering and Manufacturing Corp, Pittsfield, Mass.
f. SFM3000 Mass Flow Meter, Sensirion AG, Stäfa, Switzerland.
g. Hallowell Engineering and Manufacturing Corp, Pittsfield, Mass.
h. Excel 2016, Microsoft Corp, Redmond, Wash.
i. SAS, version 9.3, SAS Institute Inc, Cary, NC.

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