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RESPIRATION AND THE AIRWAY

Delivery of tidal volume from four anaesthesia ventilators during volume-controlled ventilation: a bench study†

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Editor's key points

- This study investigated the accuracy of delivered tidal volume in four new ventilators under different conditions.
- Set and delivered tidal volumes differed when compliance and resistance were changed, although the effect of fresh gas flow was less.
- Some of the new ventilators tested were more accurate than others.
- The clinical significance of these findings is uncertain, but anaesthetists should be aware of the potential for imprecision.

Background. Tidal volume (V_T) must be accurately delivered by anaesthesia ventilators in the volume-controlled ventilation mode in order for lung protective ventilation to be effective. However, the impact of fresh gas flow (FGF) and lung mechanics on delivery of V_T by the newest anaesthesia ventilators has not been reported.

Methods. We measured delivered V_T (V_{TI}) from four anaesthesia ventilators (Aisys™, Flow-i™, Primus™, and Zeus™) on a pneumatic test lung set with three combinations of lung compliance (*C*, ml cm H_2O^{-1}) and resistance (*R*, cm H_2O litre^{-1} s^{-2}): C60R5, C30R5, C60R20. For each *CR*, three FGF rates (0.5, 3, 10 litre min^{-1}) were investigated at three set V_Ts (300, 500, 800 ml) and two values of PEEP (0 and 10 cm H_2O). The volume error $= [(V_{TI} - V_{Tset})/V_{Tset}] \times 100$ was computed in body temperature and pressure-saturated conditions and compared using analysis of variance.

Results. For each *CR* and each set V_T, the absolute value of the volume error significantly declined from Aisys™ to Flow-i™, Zeus™, and Primus™. For C60R5, these values were 12.5% for Aisys™, 5% for Flow-i™ and Zeus™, and 0% for Primus™. With an increase in FGF, absolute values of the volume error increased only for Aisys™ and Zeus™. However, in C30R5, the volume error was minimal at mid-FGF for Aisys™. The results were similar at PEEP 10 cm H_2O.

Conclusions. Under experimental conditions, the volume error differed significantly between the four new anaesthesia ventilators tested and was influenced by FGF, although this effect may not be clinically relevant.

Keywords: measurement techniques, ventilation volumes; model, ventilatory mechanics; ventilation, fresh gas flow; ventilation, mechanical; ventilators

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Anaesthesia ventilators must adapt to various lung mechanics and maintain the same ventilatory settings as those often selected for patients in intensive care unit (ICU), such as PEEP or tidal volume (V_T). In the volume-controlled ventilation (VCV) mode, gas compression and hygrometric conditions should be properly managed by the ventilators.[1] Dry (0% relative humidity) and cold (15°C) gas must be conditioned to enter the lung as water-saturated (47 mm Hg and 100% relative humidity) and warmed (temperature close to 37°C). Humidifying and heating the inspired gas mixture increases the gas volume. Therefore, gas compression and thermal expansion act in opposite ways. The situation is further complicated depending on whether the gas volume is expressed as ambient temperature–pressure dry (ATPD) or body temperature–pressure-saturated (BTPS) in the ventilator. By simply changing the scale, the amount of volume would change by an average of 10%.[2] When a ventilator is switched on, the units of gas volume are set by default on the ATPD, BTPS, or body temperature pressure dry (BTPD) scale. It has been shown that the actual V_T may significantly differ from the set V_T in modern ICU ventilators.[2 3] One reason for this is that algorithms differ between different ventilators.

Anaesthesia ventilators have specific features. Fresh gas flow (FGF) is used to deliver oxygen and anaesthetic gases and to remove CO_2. The product of FGF and inspiratory time gives the fresh gas volume to be added to the set V_T for ventilators that are not FGF decoupled. Varying FGF would result in

† This article is accompanied by Editorial III.

variations of the total delivered V_T. In order to render the delivered V_T equal to the set V_T, ventilators use an FGF decoupling system that diverts FGF or modulates the set V_T depending on the set FGF. Automatic compensation for gas compression improves the V_T accuracy of ventilators without this type of algorithm.[4–7] Because the effect of FGF on V_T has not been widely investigated and algorithm and software versions regularly improve anaesthesia ventilators, we launched a bench study to measure the delivered V_T from four anaesthesia ventilators. We aimed to investigate the impact of the FGF rate on V_T during VCV with the primary hypothesis being that the FGF rate did not influence it.

Methods

Equipment

The set-up comprised: (i) brand new ventilators, fully checked by the manufacturer: Aisys™ (GE Datex-Ohmeda, München, Germany), Flow-i™ (Maquet, Solna, Sweden), and Primus™ and Zeus™ (Dräger, Lübeck, Germany) (Table 1); (ii) one-lung configuration test lung (TTL, Michigan Instruments, Grand Rapids, MI, USA) with adjustable compliance (*C*, ml cm^{-1} H_2O) and parabolic resistors (*R*, cm H_2O litre^{-1}s^{-1}); (iii) a double-limb ventilatory circuit (Smoothbore breathing system, 1.6 m limb, Intersurgical, Workingham, UK); (iv) a data acquisition system containing a pneumotachograph (Fleish 4 pneumotachograph, Fleish, Lausanne, Switzerland) for airflow (*V′*) measurement, and a straight connector (VBM Medizintechnik GmbH, Sulz a. N., Germany) as a port for airway opening pressure (Pao) measurement. The pneumotachograph was inserted between the Y-piece of the ventilatory circuit and the Pao port. *R* is between the Pao port and the TTL. Pneumotachograph was linear over the −10 to +10 litre s^{-1} *V′* range. *V′* and Pao ports were connected to piezoresistive transducers (BD Gabarith™, Vogt Medical Vertrieb GmbH, Karlsruhe, Germany). Signals were amplified, sent to analogue–digital hardware (Biopac MP150, BIOPAC Systems, Inc., Goleta, CA, USA), and recorded at 400 Hz (AcqKnowledge® 3.8.2, BIOPAC Systems, Inc.).

Protocol

The experiment was conducted over a 1 day period for each ventilator. Room temperature, barometric pressure, and hygrometry were measured on the day of investigation [DPM4 (QA-PT), Fluke Corporation, Everett, WA, USA]. Before the experiment, a complete automated check was performed on the ventilator before use, followed by a 30 min stabilization period. Piezoresistive transducers were calibrated before measurements.

Procedure

Each ventilator was set to VCV with constant inflation flow, inspired oxygen fraction 40%, insufflation time 1 s, insufflation to exsufflation time ratio 1/3, and a respiratory rate of 14 cycles min^{-1}. Zeus™ sets a 0.2 s inspiratory pause by default.

First, three combinations of *C* and *R* were applied in a random order: C60R5 (normal lung), C30R5 (reduction in lung compliance), and C60R20 (increased airway resistance). Then, for each *CR* combination, PEEP 0 cm H_2O (ZEEP) (except for Zeus™ which provided 2–3 cm H_2O PEEP by default) was applied. On ZEEP, low (0.5 litre min^{-1} except for Zeus™ in which the lowest FGF was 0.65 litre min^{-1}), middle (3 litre min^{-1}), and high (10 litre min^{-1}) FGF rates were administered. At each FGF rate, V_Ts of 300, 500, and 800 ml were delivered. Each V_T was tested with and without a 1 s end-inspiratory pause. With pause, the insufflation to exsufflation time ratio went to 1/2. Zeus™ was not tested without pause as mentioned above. Each V_T and pause combination was administered randomly at each FGF rate. The same steps were repeated at PEEP 10 cm H_2O (PEEP10). At each step, a 5 min stabilization period was followed by a 1 min continuous recording of Pao and *V′*. Each recording started with a 5 s end-

Table 1 Main characteristics of the four anaesthesia ventilators investigated and physical ambient conditions at the time of present investigation. FGF, fresh gas flow; ATPD, ambient temperature pressure dry; BTPD, body temperature pressure dry; BTPS, body temperature–pressure-saturated, V_T, tidal volume

	Aisys™	Flow-i™	Primus™	Zeus™
Manufacturer	GE	Maquet	Dräger	Dräger
Software version	7.01	1.02	4.3	4.01
Gas delivery system	Ascending bellows-in-box	Volume reflector	Piston-driven	Turbine
FGF decoupling system	No (fresh gas compensation)	Yes	Yes	Yes
Set gas conditions	ATPD	BTPD	BTPS	BTPS
Built-in flow meter	Variable orifice flow sensors	Hot wire	Hot wire	Hot wire
Accuracy on V_T measurement provided by the manufacturer in the V_T range presently investigated	(<7%)	(15%)	(5–10%)	(10%)
Circuit compliance (ml cm^{-1} H_2O)	1.28	1.54	1.60	1.91
Circuit temperature (°C)	22.8	20.9	21.1	24.0
Room temperature (°C)	23.2	20.9	21.1	25.3
Room air pressure (mm Hg)	755	741	741	742
Room relative humidity (%)	50	Missing	50	46

inspiratory pause in order to check for leaks in the experimental set-up. At the end of the last step for each *CR*, condition zero V' was recorded for 30 s. The last three respiratory cycles of each record were analysed. At the end of the experiment, the temperature was measured at the Y-piece.

Data analysis

Data were analysed offline (AcqKnowledge® 3.8.2, BIOPAC Systems, Inc.). V_T was measured during insufflation (V_{TI}) from the numerical integration of the V' signal after subtracting the zero V' reference value. V_{TI} was normalized in BTPS conditions as follows:

$$V_{TI}(\text{BTPS}) = V_{TI}(\text{ATPD}) \times \left(\frac{\text{PB} - P\text{H}_2\text{O}}{\text{PB} - 47}\right) \times \frac{310}{273} + T(^\circ\text{C})$$

where PB is the ambient pressure, PH$_2$O the partial pressure of water in saturated air at circuit temperature, and T the circuit temperature.

V_{TI} was expressed as the volume error according to:

$$\text{Volume error} = \left[\frac{V_{TI} - V_{Tset}}{V_{Tset}}\right] \times 100$$

The primary endpoint was the effect of FGF on the volume error between the ventilators in each *CR* condition at each PEEP level and set V_T. Lung mechanics conditions, PEEP, and V_T were analysed separately. For each *CR*–PEEP–set V_T combination, with end-inspiratory pause, the ventilator effect, the FGF effect, and their interaction on the volume error were tested using analysis of variance (ANOVA). Multiple pairwise comparisons were performed using Tukey's HSD procedure.[8]

We wanted to know which pressure, among the peak and plateau Pao, was used by the algorithm to compensate for the compliance of the ventilator circuit. For that, we decided to analyse the effect of end-inspiratory pause in the C60R20 condition only because the latter would be most likely to enhance the difference between the peak and plateau Pao. In order to take into account the number of tests, we applied the Bonferroni correction.[9] One hundred and eight combinations were generated (3 CR×2 PEEP×2 inspiratory pause×3 V_T ×3 FGF). The level of statistical significance set in ANOVA was computed by dividing 0.05 by the square root of 108, which is 0.005. *Post hoc* comparisons were 324 with an end-inspiratory pause (3 CR×2 PEEP×3 V_T ×3 FGF×6 inter-ventilator comparisons) and 162 without an end-inspiratory pause (only three ventilators) resulting in a total of 486 comparisons. The level of statistical significance for each comparison was computed as 0.05 divided by the square root of 486, which is 0.002.

The distribution of the volume error was compared using the χ^2 test.

Values are expressed as mean (SD) unless otherwise stated. Statistical analysis was carried out using R software-version 2.9.0 (R Development Core Team. *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing; 2009).

Results

Unfortunately, the files pertaining to the PEEP 10 experiment with a pause for the lowest FGF rate at V_T 300 for Zeus™ and V_T 800 for Flow-i™ were unreadable on the hard disk drives of our computers, and hence, data are lacking. The physical ambient conditions at the time of the experiments are shown in Table 1.

Overall volume error

Across all ventilators and all conditions, the actual V_T varied between 279 and 347 ml for set V_T 300, 464 and 588 for set V_T 500, and 736 and 891 for set V_T 800. The mean (SD) volume error was +9.1 (2.5)% for Aisys™, +6.7 (1.4)% for Flow-i™, −1.1 (1.6)% for Primus™, and −3.1% (2.6) % for Zeus™.

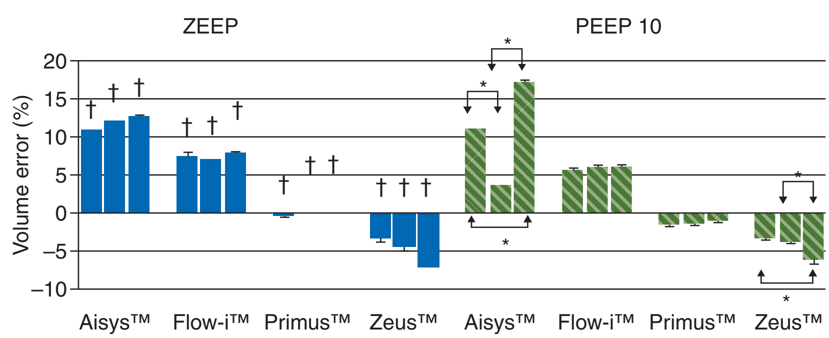

Fig 1 Effect of FGF on the volume error across four anaesthesia ventilators for a set tidal volume of 500 ml (with end-inspiratory pause) and compliance of 60 ml cm^{-1} H$_2$O. Resistance 5 cm^{-1} H$_2$O litre^{-2} on ZEEP (blue bars) and PEEP (green striped bars) 10 cm H$_2$O. For each ventilator, the left vertical bar is for low FGF, the middle vertical bar for medium FGF, and the right vertical bar for high FGF. The bars represent the mean values. $^{\dagger}P < 0.05$ *vs* the three other ventilators at a given FGF rate. $^{*}P < 0.05$.

Volume error in ZEEP with pause

In the C60R5 condition set V_T 500 (Fig. 1), the volume error was significantly different between ventilators with no FGF effect. The same was true for V_T 300 and V_T 800, except that the latter FGF rate had a statistical effect (Supplementary Table S1).

For the C60R20 mechanical condition, the results were similar to C60R5. The volume error was significantly different between Primus™ and Zeus™ for the highest FGF (0% *vs* −4%) for V_T 300 and 500.

For the C30R5 mechanical condition, the ventilator, FGF rate, and their interaction had significant effect on the volume error at each set V_T. Contrary to the two previous mechanical conditions, the volume error behaved differently for Aisys™. It was significantly and systematically lower in the middle than at two other FGF rates (Supplementary Table S1). As a result, the volume error was significantly lower at the middle FGF rate with Aisys™ than with Flow-i™.

A summary of the volume error values averaged for the three FGFs is displayed in Table 2 in terms of ventilator, CR, and PEEP level.

Effect of FGF on volume error in PEEP 10 with pause

With PEEP 10, the most striking feature was the FGF effect in Aisys™. The volume error was significantly lower with mid-FGF than for the two other FGF rates in the C60R5 condition set V_T 500 (Fig. 1). The same was true for all other conditions (Supplementary Table S2) except for set V_T 300 C60R20 and C30R5 and set V_T 500 C60R20 (Supplementary Table S2).

Effect of FGF on volume error in each ventilator

For Flow-i™ and Primus™, the volume error did not change with FGF in almost all conditions (Supplementary Tables S1 and S2). For Zeus™, when the FGF increased, the mean (SD) absolute volume error increased on ZEEP and PEEP 10 by 4.5 (0.8)% ($P<0.05$) and 4.4 (1.0)% ($P<0.05$) (Supplementary Tables S1 and S2), respectively. The differences in the volume error between the lowest and highest FGF on ZEEP and PEEP 10 were 1.4 (1.3)% and 1.3 (2.1)% ($P<0.05$).

Effect of pause on volume error in the C60R20 condition

There were significant effects on the volume error of the ventilator, FGF, pause, and their corresponding interactions (Fig. 2). Furthermore, adding a pause had opposite effects on the volume error depending on the ventilator (Fig. 2). For Aisys™ and Primus™ ventilators, the volume error significantly decreased with pause when compared with without pause regardless of the V_T. The opposite was found for the Flow-i™ ventilator (Fig. 2).

Accuracy of anaesthesia ventilators

Table 3 displays the distribution of the volume error classified into three categories over all the conditions for each ventilator. As shown, Primus™ had the highest rate in the low range of volume error and Aisys™ had the lowest rate.

Discussion

We found significant statistical differences in the volume error: (i) between ventilators, (ii) from FGF rate across ventilators, and (iii) from end-inspiratory pause.

Methodological issues

Gas volume was normalized in BTPS condition for all ventilators. None of the previous studies of anaesthesia ventilators performed this normalization and, therefore, the comparisons between ventilators were performed with different gas physical conditions. In the present study, the BTPS correction for Aisys™ and Flow-i™ resulted in an average increase in V_{TI} by 8.4% and 3.7%, respectively. No correction was made for the other two ventilators (Table 1).

Table 2 Volume error in four anaesthesia ventilators set with end-inspiratory pause at three nominal set tidal volumes and two levels of PEEP, for three conditions of lung resistance and compliance. Values are mean (standard deviation) in percentage; *C*, compliance; *R*, resistance; V_T, tidal volume; ZEEP, zero end-expiratory pressure; NA, not available. All pairwise differences between ventilators for each level of CR, set *VT*, and ZEEP are statistically significant except those indicated by the symbols. * *vs* Zeus, † *vs* Flow-i

Ventilator	*CR*	V_T 300		V_T 500		V_T 800	
		ZEEP	PEEP10	ZEEP	PEEP10	ZEEP	PEEP10
Aisys™	C60R5	11.4 (1.4)	9.5 (1.9)	12.0 (0.8)	10.8 (6.0)	9.9 (1.3)	8.5 (1.8)
	C60R20	9.6 (0.8)	9.0 (0.5)	10.2 (0.6)	9.5 (0.4)	5.2 (2.2)	9.2 (1.4)
	C30R5	8.0 (2.6)†	9.7 (0.3)	9.1 (1.1)	8.1 (1.8)	7.0 (2.2)	6.6 (1.3)
Flow-i™	C60R5	8.0 (0.2)	5.5 (0.3)	7.6 (0.5)	6.2 (0.2)	6.0 (0.6)	5.2 (0.3)
	C60R20	8.4 (0.2)	6.4 (0.4)	6.7 (0.1)	5.5 (0.1)	4.4 (0.5)	4.0 (0.1)
	C30R5	9.7 (0.4)	8.5 (0.5)	8.4 (0.2)	7.8 (0.3)	6.7 (0.4)	NA
Primus™	C60R5	0.7 (0.4)	−0.4 (0.2)	−0.1 (0.2)	−1.2 (0.3)	−1.2 (0.3)	−2.5 (0.3)
	C60R20	−0.1 (0.2)	−1.6 (0.2)	−1.6 (0.2)	−2.8 (0.2)	−3.5 (0.2)	−4.7 (0.2)*
	C30R5	0.8 (0.3)	1.4 (0.3)	−0.1 (0.5)	−0.2 (0.3)	−1.6 (0.4)	−0.9 (2.0)
Zeus™	C60R5	−5.2 (1.6)	−4.9 (1.7)	−4.9 (1.8)	−4.4 (1.4)	−5.2 (2.2)	−5.2 (1.9)
	C60R20	−1.4 (2.0)	NA	−2.4 (1.8)	−2.4 (1.9)	−3.8 (2.3)	−3.9 (2.1)
	C30R5	0.1 (2.1)	−0.9 (2.5)	−1.1 (2.3)	−1.7 (2.1)	−2.6 (2.6)	−3.3 (2.6)

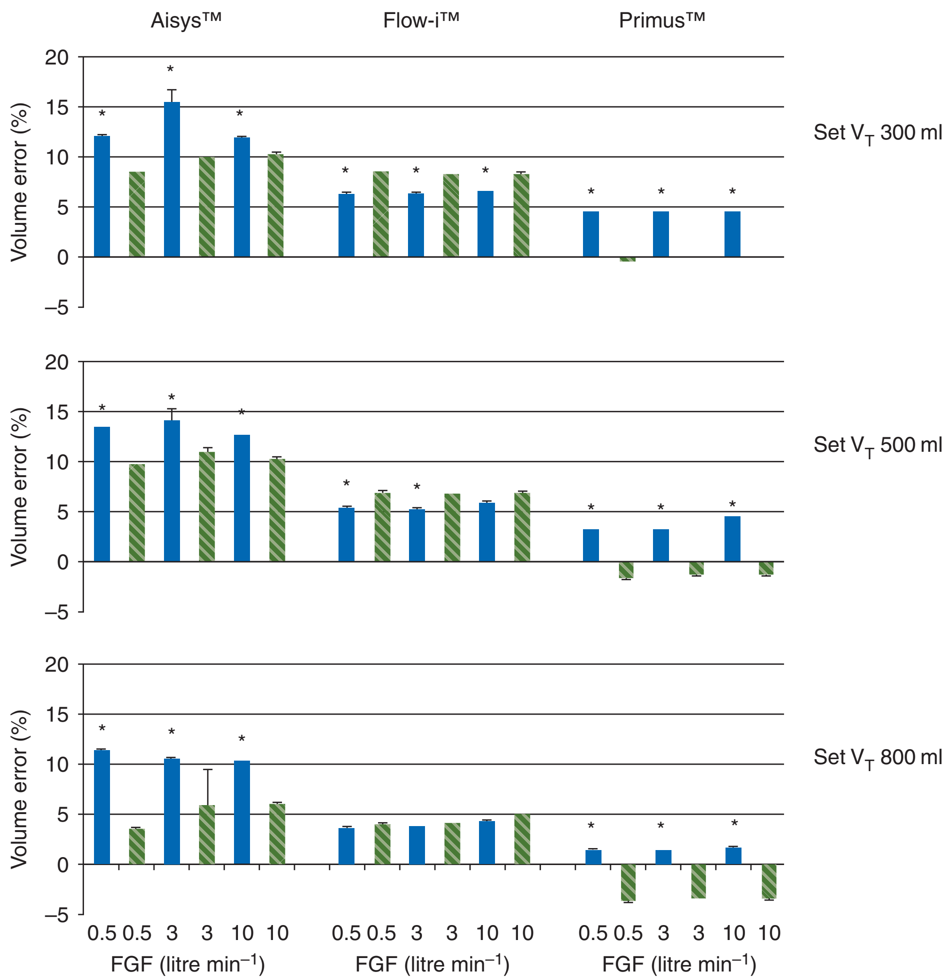

Fig 2 Effect of end-inspiratory pause on the volume error at a different FGF in three anaesthesia ventilators at compliance 60 ml cm^{-1} H_2O and resistance 20 cm^{-1} H_2O $litre^{-2}$ for three set tidal volumes (V_T). The bars represent the mean values for no pause (blue) and pause (green striped). * $P < 0.05$ *vs* pause.

Table 3 The occurrence of the volume error in three categories across anaesthesia ventilators over all the conditions investigated

	≤5%	>5 to ≤10%	>10%
Aisys™	16 (4.9%)	115 (35.5%)	193 (59.6%)
Flow-i™	116 (36.1%)	204 (63.6%)	1 (0.3%)
Primus™	323 (99.7%)	1 (0.3%)	0 (0%)
Zeus™	126 (79.2%)	33 (20.8%)	0 (0%)
P-value (χ^2 test)		<0.0001	

We used the Bonferroni correction to correct for multiple comparisons in our data analysis. The manner in which the data are handled has been criticized.[9] It is too conservative and can miss significant differences. However, in the present experiment, virtually all differences were statistically significant. This was due to the very low standard deviations resulting from the very low variability between measurements for a given variable for this type of *in vitro* experiment. So, our goal was to minimize the number of positive tests.

Difference in the engineering system and the present findings

The difference in the magnitude of the volume error across ventilators may be explained by differences in the engineering system used (Table 1). However, it is unclear which element, among the electronic system, algorithm, FGF decoupling system, accuracy and position of the flow meters, and type of gas delivery system, would determine the accuracy of V_T delivery. In bench studies, the precision in delivered V_T was greater with a piston than with a turbine or a bellows-in-box, owing to a low-compliance system, leak compensation, and rigid piston design.[6 10 11]

Aisys™ is a pneumatically driven ventilator in which the gas delivery unit is an ascending bellows-in-box with fresh gas compensation. The closer the volume delivered per minute and FGF, the smaller the volume error. FGF is not decoupled, that is, fresh gas is primarily delivered to the inspiratory circuit, and then the ventilator electronically computes the required volume to be added to the fresh gas in order to get the set V_T. Even though electronic devices are increasingly accurate, they may be challenged in extreme conditions, as Aisys™ had the highest volume error in the present study. This result is in disagreement with that of a previous bench study in which the average volume error ranged between −5% and +6%.[12] One explanation for this inconsistency could be the gas volume expression, which was not provided.[12] With Flow-i™, the gas delivery system, referred to as the volume reflector, is a circle system with a non-compliant tank of gas of about 1.2 litres. Exhaled gases are recycled in the volume reflector and pure oxygen is used to push expired gas into the inspired flow. Its rigidity means that overflows are avoided and ensures that the tank is always filled, even in the event of a leak. In fact, the volume error magnitude was lower than in Aisys™ but higher than in Primus™ and Zeus™. Primus™ is a piston ventilator with a fresh gas decoupling system. Piston pitch is about 5 µl. This accuracy is consistent with our observations showing that volume error is very low (about 1%) with Primus™. Zeus™ is a turbine ventilator. It works with a closed-circuit system, which delivers the adequate gas mixture at the lowest FGF. The turbine system works as a pressure source whose accuracy fully depends on flow-meter precision. Indeed, the volume error with Zeus™ was in-between that with Flow-i™ and Primus™, about 3%.

The absolute volume error value exhibited two distinct patterns with increasing FGF. It increased in Aysis™ and Zeus™ but did not change in Primus™ and Flow-i™. With Aisys™, the overestimation of V_T went up with the increase in FGF. The underestimation of V_T with Zeus™ with increasing FGF could be explained by the Venturi effect in the circuit as shown in turbine-driven transport ventilators.[13]

Effect of pause set at the ventilator at end-inspiration

The pause effect on V_T has not been previously investigated with anaesthesia ventilators. With pause, the following points are expected to change in actual V_T: (i) no change, if the algorithm of compensation for ventilator circuit compliance targets peak Pao and if inspiratory flow does not change; (ii) increase, if the algorithm targets plateau Pao; (iii) reduction, if inspiratory flow diminishes as a result of pause, or if pause impairs the working of the algorithm. With Aisys™ and Primus™, we found that V_T decreased with pause. The fact that inspiratory flow did not change with and without pause suggests no such algorithm in these ventilators or specific functioning of the algorithm that does not follow the above rules. Another explanation would be that the increase in the mean Pao we found (by 70%, not shown), resulting from the reduction in exsufflation time, would compress gas in the ventilator circuit, which was not sensed by the algorithm which eventually failed to increase V_T. With Flow-i™, V_T increased with pause, suggesting that the algorithm targets plateau Pao for set V_T 300 and 500 ml. In contrast, V_T did not change for set V_T 800 ml, suggesting that the algorithm targeted peak Pao. These findings were consistent over the FGF range.

Accuracy of the anaesthesia ventilators on the bench

When compared with the manufacturers' specifications (Table 1), we found that the Aisys™ had the lowest accuracy when the volume error was >7% in almost all conditions (Table 2). Furthermore, the volume error >10% was obtained in almost 60% of all measurements for this ventilator (Table 3). For the Flow-i™, we found that the volume error consistently lower than the 15% provided by the manufacturer (Tables 1–3). The same applied for the Zeus™ system (Tables 1–3). The Primus™ had the highest accuracy as the volume error was consistently lower than the threshold provided by the manufacturer (Tables 1 and 2) and we found that the volume error exceeded 5% in only one instance (Table 3). There are some circumstances where there was little difference between the ventilators. These circumstances are set V_T 800 C60R20 and mostly pertain to the Primus™ and Zeus™ ventilators. Some practitioners may find any error <10% acceptable. From our Table 3, it can be seen that this was the case for all ventilators except for Aisys™.

Clinical implications

Artificial ventilators, when used in ICU patients with abnormal lungs, must continue to provide lung protective mechanical ventilation and low V_T and prevent ventilator-induced lung injury (VILI).[14 15]

Furthermore, patients with normal lungs who have undergone general anaesthesia and mechanical ventilation are also at risk for VILI.[16] Therefore, it is important to reduce V_T in these patients, as suggested by some investigations.[17 18] Michelet and colleagues[17] prospectively compared two ventilatory strategies during general anaesthesia for elective oesophagectomy in patients with normal lungs: V_T 9 ml kg^{-1} with ZEEP and V_T 5 ml kg^{-1} with PEEP of 5 cm H_2O. The respiratory rate was set at 12 bpm and F_{IO_2} 50% in both groups. These settings were applied during the single-lung ventilation part of surgery. The low V_T strategy resulted in a shorter duration of mechanical ventilation and lower plasma concentrations of inflammatory cytokines. Fernandez-Perez and colleagues[18] found that large V_T (8.3 *vs* 6.7 ml kg^{-1}) was the single main risk factor for developing postoperative respiratory failure after pneumonectomy in 170 patients (odds ratio 1.56 per ml kg^{-1} increase). By using the extreme values of the volume error in the present experiment (−8% to +17.5%), we found that a target set V_T of 6 ml kg^{-1} resulted in an actual V_T between 5.5 and 7 ml kg^{-1}. Therefore, if the clinician prescribes V_T of 6 ml kg^{-1} having in mind lung protection, the lung can receive a different V_T. It should be stressed that Primus™ was the most accurate to deliver a set V_T.

Limitations and strengths

Limitations of our study are that bench testing cannot mimic *in vivo* conditions, that we only used VCV, and we tested a single anaesthesia ventilator from each manufacturer. The same ICU ventilator delivered different V_T over time in patients.[19]

However, experiments can be performed under carefully controlled conditions and with a wide range of combinations of settings in a bench-top study. The variability of V_T measurements was very small in our study. We used a gas mixture of 40% oxygen to be as close as possible to clinical practice.

In summary, using the experimental conditions described, we found that V_T delivery from new anaesthesia ventilators differed significantly between them and was influenced by FGF and end-inspiratory pause. These effects may not be clinically relevant.

Supplementary material

Supplementary material is available at *British Journal of Anaesthesia* online.

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Declaration of interest

None declared.

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