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Comparison of ventilation techniques for compensation of mask leakage using a ventilator and a regular full-face mask: A bench study

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ABSTRACT

Background: The use of noninvasive ventilation (NIV) during and after extubation is common. We designed this study to determine the optimal strategy to compensate for mask leaks and achieve effective ventilation during NIV by comparing commonly used operating room ventilator systems and a regular facemask.

Methods: We tested four operating room ventilator systems (Dägger Zeus, Dägger Apollo, Dägger Fabius Tiro, and General Electric Healthcare Carestation 650) on a lung model with normal compliance and airway resistance and evaluated pressure control ventilation (PCV), volume control ventilation (VCV), and AutoFlow mode (VAF). We set the O_2 flow at 10 L/min and the maximal flow at 13, 16, or 26 L/min. We simulated five leak levels, from no leak to over 40 L/min (I to V levels), using customized T-pieces placed between the lung model and the breathing circuit. We recorded the expired tidal volume (Vte) from the lung model and peak inspiratory pressure via two flow/pressure sensors that were placed distally and proximally to the T-pieces.

Results: 1. Comparison of four ventilators: with any given ventilation mode, an increase in leak level caused a decrease in Vte. With PCV, only Zeus produced Vte larger than 150 ml at leak level V. 2. Effect of ventilation mode on Vte: across all four ventilators, PCV resulted in a higher Vte than VCV and VAF ($P < 0.01$). PCV mode with all ventilators at leak level II provided Vte values that were equal to or greater than those obtained with no leak. 3. Effect of O_2 flow on Vte Using PCV mode: only Carestation 650 Vte at leak level II during PCV were significantly greater with 16 L/min O_2 flow compared with 10 L/min O_2 flow ($P < 0.01$). 4. Actual leak: increasing the O_2 flow from 10 L/min to the maximum O_2 flow dramatically increased the real leak with all 4 ventilators at any fixed leak level ($P < 0.01$). 5. Preset PIP vs. actual PIP with PCV: at low preset PIP and leak levels such as leak II and III, the discrepancy between preset PIP and actual PIP was small. The disparity between the preset and actual PIP grew when the target PIP and the leak level were raised.

Conclusion: For NIV using a mask, the ventilator is preferred whose Pressure generator is Turbine, the PCV mode is preferred in the ventilation mode and the oxygen flow is set to 10 L/min or maximum oxygen flow.

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1. Introduction

Noninvasive ventilation (NIV) is safe and effective for many patients with respiratory failure of varied etiologies [1–4] and is one of measures [5,6] used to treat a known difficult airway. Ventilators and masks specifically designed for NIV or Intensive Care Unit (ICU) ventilators are normally used to provide NIV, mainly due to their ability to compensate for mask leak [7–10]. These ventilators have maximum airflow rates of 120–180 L/min during inspiration [11,12]. NIV is routinely utilized in the operating room for ventilatory support, either for short mask breathing during anesthesia or immediately post-surgery; however, ICU ventilators and masks specialized for NIV are not always readily available in the operating room. Using a standard facemask with an anesthetic ventilator for NIV presents a number of difficulties, the most notable of which are mask leaks and the ventilator's limited capacity to correct for mask leaks. Although several efficient strategies have been established to provide appropriate mask ventilation [13], it is crucial to find the optimal approach for NIV with conventional facemasks and operating room ventilators. To the best of our knowledge, this was the first study to evaluate operating room ventilator-based ventilation techniques for addressing circuit leaks during NIV.

The aims of this study were: 1) to identify the optimal ventilation strategy to provide effective mask ventilation using an operating room ventilator and a regular mask; and 2) to compare the effectiveness of NIV using four commonly used operating room ventilators. The primary endpoint of this bench study was expired tidal volume (Vte), a surrogate measure for effective leak compensation.

2. Methods

Using a two-compartment lung model (Dual adult TTL training/experimental lung, Model 1600, Michigan Instruments Inc., MI, USA), we compared the performance of four different operating room ventilators, Dägger Zeus, Dägger Apollo, Dägger Fabius Tiro (Dägger, Lübeck, Germany), and General Electric Healthcare Carestation 650 (GE Healthcare, Madison, WI, USA) (details are shown in Table 1). The flow-generating systems of Dägger Zeus is a turbine which generates the pressure to deliver a corresponding flow to the patient during inspiration. When circuit/mask leak is present, the turbine is repeatedly requested to increase the fresh gas flow to compensate inspiratory flow. Dägger Apollo and Dägger Fabius Tiro are piston ventilators with different max inspiratory flow (Table 1). The rigid coupling between the piston and its drive mechanism allows for fine control over the movement of the piston and continuous adjustment of inspiratory flow to maintain the desired inspiratory pressure. General Electric Healthcare Carestation 650 belongs to bellows ventilators which utilized a pressurized gas to intermittently compress the bellows and the bellows in turn delivered fresh gas to ventilate patients. The tidal volume displaced by the bellows varied. The variable levels of mask leak were simulated using customized T-pieces. The experimental setup and design of T-pieces are shown in Fig. 1.

2.1. Lung model and ventilatory settings

The lung model was adjusted to simulate the respiratory mechanics of a healthy adult: a functional residual capacity of 1020 ml, anatomical dead space of 150 ml, compliance of 50 ml/cmH_2O, and airway resistance of 5 cmH_2O/L/second. A customized breathing circuit (Hudson, Temecula, California) was used to link the lung model to the operating room ventilators. We inserted the T-pieces, simulating variable levels of mask leakage between the breathing circuit and the model lung. For each ventilator, we evaluated three ventilation modes without positive end-expiratory pressure (PEEP). 1. Volume-controlled ventilation (VCV), is a time-cycled, volume-targeted ventilation mode commonly available on all operating room ventilators. 2. Pressure-controlled ventilation (PCV), is another commonly seen mode. The anesthesia provider sets the inspiratory pressure, inspiratory time and respiratory rate. With every breath, the ventilator delivers an inspiratory flow until the preset pressure is achieved. 3. AutoFlow mode (VAF), is available in some newer anesthesia machines with the aim of combining the advantages of both PCV and VCV. The aim is the delivery of the desired tidal volume at the lowest possible inspiratory pressure with a decelerating inspiratory flow pattern. VAF targets a tidal volume by varying pressure up to3 cm H_2O up or down each breath based on the actual tidal volume delivered in the previous breath. In this study, ventilatory settings was PCV with preset peak inspiratory pressure (PIP) of 10, 15, 20, or 25 cmH_2O; VCV or VAF with preset tidal volumes of 500, 750, 1000, or 1250 ml. The respiratory rate was set at 15 breaths per minute, I:E ratio at 1:1, and raise time was 0.5 s. O_2 flow was set at 10 L/min, and maximal flow (the highest O_2 flow rate the ventilator could provide) was set at 13 L/min for Apollo, 16 L/min for Carestation 650, and 26 L/min for Zeus and Fabius Tiro ventilators. VAF was not tested in the Fabius Tiro and Carestation 650, as these operating room ventilators do not have VAF mode.

Table 1
Characteristics of the four operation room ventilators.

	Pressure generator	Software	Option of VAF mode	Maximal O_2 Flow (L/min)	Inspiratory Flow (L/min)
Zeus	Turbine	1.1n	Yes	26	0–180
Apollo	Electric piston	4.5n	Yes	13	0–150
Fabius Tiro	Electric piston	2.1n	No	26	10–75
Carestation 650	Bellows	1.0n	No	16	0–120

Note: VAF: auto-flow mode; maximal flow: the highest O_2 flow rate the ventilator could provide and was measured by flow/pressure sensor.

2.2. Leak levels

We placed customized T-pieces (a calibrated hole with a diameter of 4 mm at the distal end of each T-piece) between the lung model and the distal end of the breathing circuit to simulate variable levels of mask leak. We created leak levels I, II, III, IV, and V by opening 0, 1, 2, 4, and 6 T-pieces, respectively. The leak rates for these levels at a constant pressure of 5 cmH_2O were 0, 15, 29, 50, and 66 L/min, respectively.

2.3. Variables and evaluation

Vte from the lung model was recorded via the distal flow/pressure sensor (Fig. 1). Inspiratory flow rate, inspiratory volume, and PIP were measured with the proximal flow/pressure sensor. The leak volume was calculated by subtracting Vte from the inspiratory volume. The sensor's data gathering rate was 100 samples per second, and the maximum flow rate that could be measured was 180 L/min. We repeated the measurement at each ventilatory setting and leak level five times. The mean of the five measurements was used for the final analysis.

2.4. Data collection and statistical analysis

Vte, PIP, and leak flow rate were continuously collected at each ventilatory setting, which lasted for 1 min (total of 15 breaths) in order to achieve stabilization. The mean of the last five consecutive breaths obtained at each ventilatory setting was used as a single data point. Each trial was repeated five times on five different days. All values were reported as the mean (±SD) of the corresponding parameters of the five measurements. For comparing the effects of ventilation modes, we used one-way analysis of variance for each ventilator at a given ventilatory setting and leak level. For comparing the effects of ventilators in the same ventilation mode, one-way analysis of variance was used. Post hoc analysis was performed with Tukey's exact test if the analysis of variance reached significance. Paired *t*-test was used for comparing the effect of fresh gas flow rates. Statistical analysis was performed with the statistical software package PASW Statistic 18 (SPSS, Chicago, IL). $P < 0.05$ was considered statistically significant. We reported Vte differences only if they were both statistically significant ($P < 0.05$) and clinically important (difference in Vte >10% and >50 ml).

3. Results

3.1. Comparison of four ventilators

There were no significant differences in Vte at no leak (leak level I) among the four ventilators regardless of the ventilatory setting or ventilatory mode (Table 2) ($P > 0.05$). With any given ventilation mode, an increase in leak level caused a decrease in Vte. Vte was not measurable at leak level V in all four ventilators with VCV and at leak levels III–V in the Carestation 650 ventilator in any of the ventilation modes (Table 2). With PCV, only Zeus produced Vte larger than 150 ml at leak level V (Fig. 2).

3.2. Effect of ventilation mode on Vte

Table 2 demonstrates that, across all four ventilators, PCV resulted in a higher Vte than VCV and VAF, and the difference were statistically significant ($P < 0.05$). PCV with all ventilators at leak level II provided Vte values that were equal to or greater than those obtained with no leak. Actually, PCV overcompensated, and the Vte at leak level II was statistically higher than the Vte at no leak (leak level I) ($P < 0.05$). Except for the Carestation 650, Vte remained close to 50% of that with no leak, even at leak level III. With VCV, 50% of the no-leak Vte happened at level II of leakage. VAF provided Vte that was equivalent to that of VCV for the Zeus and Apollo ventilators with VAF functionality (Table 2).

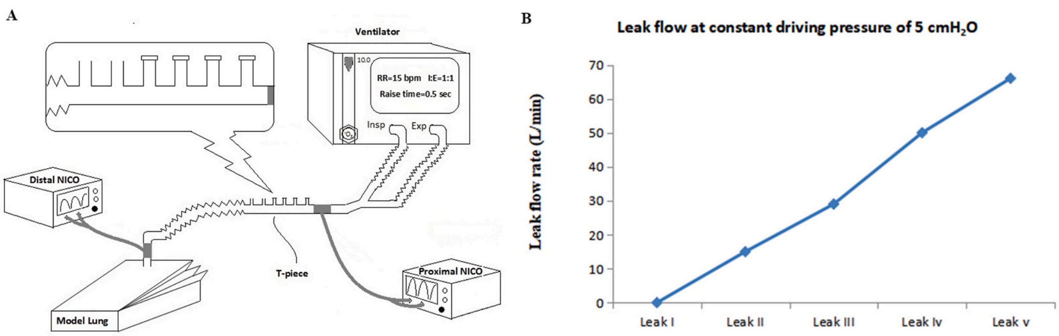

Fig. 1. Experimental setup (A) and actual flow rate (B) of the T-pieces at 5 preset leak levels and constant driving pressure of 5 cmH_2O.

Table 2
Expired tidal volume at O_2 flow of 10 L/min and maximal O_2 flow.

Ventilator	Modes	Ventilatory settings	Leak level				
			I	II	III	IV	V
O2 flow=10 L/min							
Zeus	PCV	10 cmH2O	442 ± 1	480 ± 0	415 ± 1	249 ± 2	155 ± 3
		15 cmH2O	744 ± 1	792 ± 2	555 ± 1	286 ± 1	189 ± 1
		20 cmH2O	1029 ± 2	877 ± 9	589 ± 5	295 ± 3	191 ± 4
		25 cmH2O	1326 ± 1	1228 ± 15	600 ± 2	305 ± 3	197 ± 1
	VCV	500 ml	436 ± 4	158 ± 11*	–	–	–
		750 ml	659 ± 2	325 ± 3*	106 ± 5*	–	–
		1000 ml	893 ± 4	491 ± 3*	232 ± 16*	–	–
		1250 ml	1213 ± 2	664 ± 5*	272 ± 8*	95 ± 1*	–
	VAF	500 ml	462 ± 3	170 ± 1*	170 ± 1*	123 ± 2*	–
		750 ml	723 ± 3	216 ± 2*#	181 ± 3*#	95 ± 3*	–
		1000 ml	979 ± 3	335 ± 7*#	189 ± 2*	94 ± 2*	40 ± 1*
		1250 ml	1229 ± 3	490 ± 8*#	272 ± 12*	93 ± 1*	41 ± 1*
Apollo	PCV	10 cmH2O	487 ± 11	540 ± 2 ø	355 ± 1 ø	184 ± 5 ø	101 ± 1 ø
		15 cmH2O	768 ± 10	830 ± 2	348 ± 1 ø	200 ± 1 ø	111 ± 4 ø
		20 cmH2O	1050 ± 3	778 ± 1 ø	374 ± 3 ø	227 ± 3 ø	121 ± 1 ø
		25 cmH2O	1224 ± 2 ø	773 ± 1 ø	391 ± 1 ø	192 ± 2 ø	131 ± 1 ø
	VCV	500 ml	470 ± 4	167 ± 3*	49 ± 1*	–	–
		750 ml	711 ± 1	342 ± 4*	157 ± 4*	–	–
		1000 ml	953 ± 3 ø	525 ± 6*	280 ± 0*	64 ± 3*	–
		1250 ml	1201 ± 1	713 ± 2 ø	331 ± 1* ø	148 ± 1*	–
	VAF	500 ml	498 ± 4	163 ± 0*	166 ± 1*#	133 ± 2*	101 ± 1
		750 ml	745 ± 10	323 ± 0*ø	158 ± 2*	141 ± 2*	127 ± 1
		1000 ml	1003 ± 4	503 ± 2*ø	238 ± 2*	145 ± 1*#	120 ± 2
		1250 ml	1238 ± 2	677 ± 2*ø	262 ± 1*#	140 ± 1*	125 ± 1
Fabius Tiro	PCV	10 cmH2O	448 ± 4	363 ±1øƒ	321 ± 2 ø	192 ± 1 ø	109 ± 2
		15 cmH2O	695 ± 2	600 ± 2 øƒ	539±3ƒ	317±2ƒ	141 ± 1
		20 cmH2O	977 ± 4	806 ± 4	668 ± 1 øƒ	321±1ƒ	137 ± 2
		25 cmH2O	1260 ± 4 ø	947 ± 2 øƒ	686 ± 1 øƒ	320±1ƒ	139 ± 1
	VCV	500 ml	489 ± 24	192 ± 1*	–	–	–
		750 ml	748 ± 10 ø	372 ± 4*	155 ± 2*	–	–
		1000 ml	993 ± 15 ø	560 ± 11* ø	291 ± 3* ø	52 ± 1*ƒ	–
		1250 ml	1244 ± 18	756 ± 14* ø	434 ± 3* ø ƒ	122 ± 1*	–
Carestation650	PCV	10 cmH2O	363 ± 9 øƒ£	414 ± 12 ø ƒ	67 ± 11 ø ƒ£	–	–
		15 cmH2O	640 ± 13 øƒ	559 ± 10 ø ƒ	108 ± 8 ø ƒ£	–	–
		20 cmH2O	971 ± 15ƒ	619 ± 12 ø ƒ£	114 ± 6 ø ƒ£	–	–
		25 cmH2O	1147 ± 22 ø ƒ	667 ± 10 ø ƒ£	110 ± 13 ø ƒ£	–	–
						–	–
	VCV	500 ml	506 ± 6* ø	158 ± 8*	–	–	–
		750 ml	754 ± 7* ø	286 ± 2* ƒ£	–	–	–
		1000 ml	1003 ± 6 ø	383 ± 1* ø ƒ£	–	–	–
		1250 ml	1247 ± 9	486 ± 5* øƒ£	–	–	–
						–	–
Maximal O2 flow							
Zeus	PCV	10 cmH2O	417 ± 1	452 ± 2	408 ± 1	254 ± 1	165 ± 1
		15 cmH2O	700 ± 2	774 ± 2	563 ± 1	298 ± 2	183 ± 1
		20 cmH2O	988 ± 1	889 ± 6	577 ± 3	303 ± 3	192 ± 1
		25 cmH2O	1293 ± 1	1243 ± 5	598 ± 1	311 ± 8	205 ± 3
	VCV	500 ml	428 ± 7	135 ± 1*	–	–	–
		750 ml	663 ± 2	280 ± 2*	82 ± 2*	–	–
		1000 ml	952 ± 4	436 ± 0*	186 ± 0*	63 ± 4*	–
		1250 ml	1224 ± 18	606 ± 8*	312 ± 8*	65 ± 3*	–
	VAF	500 ml	449 ± 1	193 ± 2*	185 ± 2*	132 ± 2*	–
		750 ml	696 ± 1	243 ± 2*	202 ± 1*	107 ± 1*	–
		1000 ml	963 ± 1	332 ± 1*#	196 ± 3*	100 ± 2*	47 ± 2*
		1250 ml	1258 ± 2	515 ± 5*#	260 ± 1*#	102 ± 2*	45 ± 4*
Apollo	PCV	10 cmH2O	468 ± 1	479 ± 8	394 ± 2	169 ± 2	98±1ø
		15 cmH2O	736 ± 1	788 ± 2	383±1ø	209±1ø	123±1ø
		20 cmH2O	1024 ± 3	744±2ø	378±1ø	220±1ø	113±1ø

(continued on next page)

Table 2 (*continued*)

Ventilator	Modes	Ventilatory settings	Leak level				
			I	II	III	IV	V
		25 cmH2O	1197 ± 1	852±1ø	405±1ø	187±2ø	121±1ø
	VCV	500 ml	498 ± 1	173 ± 4*	–	–	–
		750 ml	751 ± 1	348 ± 4*ø	–	–	–
		1000 ml	962 ± 4	535 ± 6*ø	58 ± 4*ø	–	–
		1250 ml	1245 ± 4	727 ± 1*ø	145 ± 1*ø	–	–
	VAF	500 ml	509 ± 1	148 ± 1*	159 ± 1*	146 ± 2	98 ± 1
		750 ml	767 ± 3	304 ± 3*ø	144 ± 2*ø	144 ± 1*	104 ± 4
		1000 ml	1020 ± 3	491 ± 3*ø	256 ± 3*ø	134 ± 1*	125 ± 1
		1250 ml	1260 ± 11	646 ± 1*#ø	288 ± 1*#ø	143 ± 2	124 ± 1
Fabius Tiro	PCV	10 cmH2O	451 ± 2	360±3øƒ	297±1øƒ	167±2ø	87±1ø
		15 cmH2O	708 ± 1	627±1øƒ	518±1øƒ	305±2øƒ	128±1ø
		20 cmH2O	983 ± 3	858±1øƒ	654±1øƒ	307±1ø	125±1ø
		25 cmH2O	1260 ± 1	955±3øƒ	673±1øƒ	308±1øƒ	127±1ø
	VCV	500 ml	493 ± 18	199 ± 1*ø	–	–	–
		750 ml	774 ± 23	386 ± 1*ø	158 ± 1*ø	–	–
		1000 ml	1012 ± 11	577 ± 7*ø	294 ± 1*ø	–	–
		1250 ml	1257 ± 5	775 ± 8*ø	441 ± 5*ø	–	–
Carestation 650	PCV	10 cmH2O	334 ± 7 øƒ£	395 ± 11 øƒ	314 ± 2 øƒ	–	–
		15 cmH2O	601 ± 4 øƒ£	673 ± 2 øƒ	382 ± 5 ø£	–	–
		20 cmH2O	845 ± 2 øƒ£	918 ± 23 øƒ	426 ± 11 øƒ£	–	–
		25 cmH2O	1091 ± 16 ø£	963 ± 28 øƒ	447 ± 13 øƒ£	–	–
						–	–
	VCV	500 ml	511 ± 7* ø	105 ± 4*ƒ£	–	–	–
		750 ml	750 ± 3* ø	270 ± 5* ƒ£	–	–	–
		1000 ml	1000 ± 2*	432 ± 11* ƒ£	–	–	–
		1250 ml	1251 ± 4*	628 ± 6* ƒ£	–	–	–

Note: Data are presented as means ± SD from five measurements. PCV: pressure control ventilation mode; VCV: volume control ventilation mode; VAF: auto-flow mode; -: expired tidal volume not measurable. With the same ventilator at the same flow rate: *: $p < 0.01$ compared to values for PCV mode; #: $p < 0.01$ compared to values for VCV. Between ventilators at the same flow rate: ø: $p < 0.01$ compared to values at the same setting with Zeus; ƒ: $p < 0.01$ compared to values at the same setting with Apollo; £: $p < 0.01$ compared to values at the same setting with Fabius Tiro.

3.3. Effect of O_2 flow on Vte Using PCV mode

Carestation 650 Vte at leak level II during PCV were significantly greater with 16 L/min O_2 flow compared with 10 L/min O_2 flow ($P < 0.01$), but this phenomenon did not occur with any of the other three operating room ventilators, and there was no statistically significant change in Vte between the O_2 flow rates of 10 L/min and maximum O_2 flow rates ($P > 0.05$).

3.4. Actual leak

The leak rate for each of the four ventilators varied with the ventilatory setting and preset leak level. Increasing the O_2 flow from 10 L/min to the maximum O_2 flow dramatically increased the real leak with all 4 ventilators at any fixed leak level, and the difference was statistically significant ($P < 0.05$). At high leak levels and high PIP settings, the real leak flow exceeded the O_2 flow. At level V, the real leak was as high as 40.8 L per minute when the O_2 flow on the Zeus ventilator was set to its maximum of 26 L per minute.

3.5. Preset PIP vs. actual PIP with PCV

The actual PIP of the four ventilators varied at a given ventilatory setting and preset leak level. At low preset PIP and leak levels such as leak II and III, the discrepancy between preset PIP and actual PIP was small (Fig. 3). The disparity between the present and actual PIP grew when the target PIP and the leak level were raised, and the difference were statistically significant ($P < 0.01$). With maximum O_2 flow, the discrepancy between preset PIP and actual PIP at the leak level III were statistically smaller for the Carestation 650 ventilator than those for the other three ventilators ($P < 0.01$). At the highest preset PIP (25 cmH_2O) and maximum leak level (leak V) tested in this study, the real PIP reached 7.5 cmH_2O for the Zeus ventilator with maximum O_2 flow. At leak V, the actual PIP was barely detectable for the other three ventilators.

4. Discussion

The major findings of this study are as follows: 1) In every scenario, PCV provided a higher Vte than VCV and VAF. 2) The Vte of the Carestation 650 rose with increasing maximum oxygen flow but was comparable to the other three ventilators. 3) When comparing Vte to VCV, the four most popular ventilators had similar results across the board. 4) When compared to the other three ventilators, Zeus's

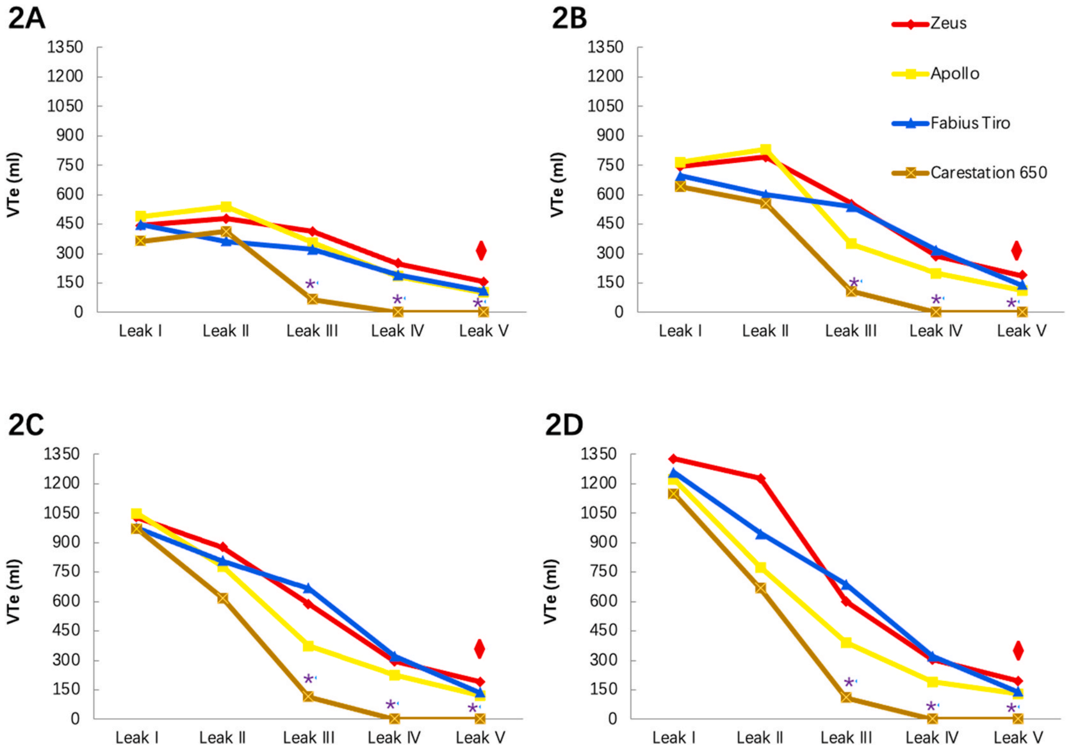

Fig. 2. Expired tidal volume obtained with 4 operating room ventilators with pressure control ventilation and variable leak levels at O_2 flow of 10 L/min.

Vte, expiratory tidal volume; Vte at preset peak inspiratory pressure of 10 (3A), 15 (3B), 20 (3C), and 25 cmH_2O (3D); *: Vte with the Carestation 650 ventilator was not measurable; ◊: only the Zeus ventilator produced tidal volume over 150 ml at leak level V. Data shown are the mean of five measurements.

performance in PCV mode stood out as the best.

NIV is commonly used in the perioperative context for the following reasons: 1. Minimally invasive surgery or procedures when a tracheostomy or laryngeal mask airway (LMA) is not expected to be required; 2. Patients who are morbidly obese and have a known difficult airway; 3. Patients who are anticipated to have difficulty in being weaned off the ventilator; 4. Pre-oxygenation; 5. Immediately after extubation [14]. This is almost exclusively conducted with an operating room ventilator and a regular facemask, as both are immediately available in the operating room. However, there are two major challenges to this approach. One is to maintain airway patency, and the other is to compensate for mask leaks. Both of them can independently affect the effectiveness of ventilation, and it is difficult to determine the effect that they have on each other. Therefore, the study of the leak compensation capabilities of operating room ventilators in human subjects in the absence of airway obstruction is extremely challenging.

One distinct benefit of conducting research like this on a bench is the ease with which varying degrees of leakage and airway blockage may be simulated in isolation. We evaluated the relationship between leak level and ventilation technique in four different operating room ventilators with a no-obstruction airway scenario. We selected Vte as our primary endpoint as it reflects the effectiveness of leak compensation, and this bench study allowed us to measure true leaks with two flow/pressure sensors. Both the ventilator's supplied volume and the Vte were measured by the proximal and distal sensors, respectively. The leak was what set them apart from one another. As a result, we could prove how the degree of leakage influenced the ventilation method used. A comprehensive understanding of such a dynamic interaction between the circuit leak and compensation using an operating room ventilator and a regular mask is clinically important, but such an experiment cannot be conducted on a human subject.

4.1. Comparison of ventilation modes

The mode of ventilation for NIV outside of the peri-operative setting is almost exclusively pressure support. Respiratory therapists are familiar with and routinely use this mode for NIV. However, caregivers may have trouble distinguishing between the various circuit leak compensation settings. Based on our findings, PCV generated greater Vte than VCV at the corresponding leak level for all four ventilators, from leak level I to leak level IV. Zeus was able to produce Vte of more than 150 ml, the anatomic dead space for an average-sized adult [15], even at leak V, the maximal leak created in this trial.

The PCV ventilator provides a constant flow of inspiratory air with every breath until the preset pressure is achieved. PCV then maintains a constant pressure during the inspiratory time by varying the delivered flow rate. When mask leak in the system is

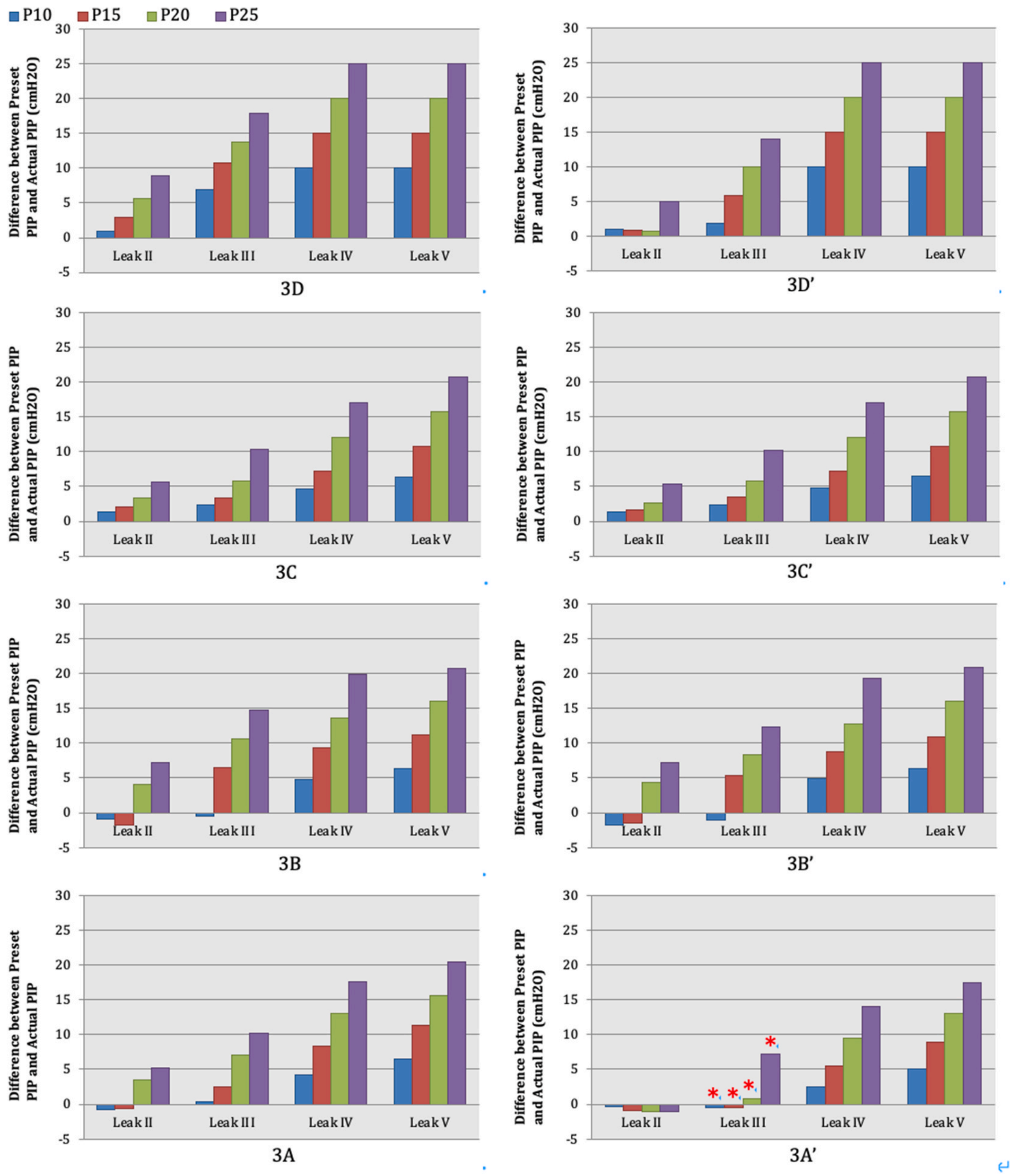

Fig. 3. Difference between preset PIP and actual PIP of the four ventilators with pressure control mode and variable leak levels.
Panels on the left side, 3A–3D, illustrate the difference between preset peak inspiratory pressure (PIP) and actual PIP at O_2 flow of 10 L/min, and panels on the right,3A′–3D′, at maximal O_2 flow. A or A′, with Zeus; B or B′, with Apollo; C or C′, with Fabius Tiro; D or D′, with Carestation 650; P, pressure control ventilation mode; Leak II-V, leak level low to high leak; the pressure differences are negative at some settings due to greater actual PIP than preset PIP: for Zeus: preset pressure 10–25 cmH_2O with leak II and 10, 15 cmH_2O with leak III; for Apollo: 10, 15 cmH_2O with leak II and 10 cmH_2O with leak III. Pressure difference increased gradually with increasing preset PIP and leak level (All $P < 0.05$). The histogram bars show the mean values of the pressure difference from five measurements. *: the discrepancy between preset PIP and actual PIP at the leak level III were smaller for the Carestation 650 ventilator with maximum O2 flow than those for the other three ventilators (All $P < 0.01$).

significant and unavoidable, targeted tidal volume may not be achieved with VCV but with PCV mode due to PCV having a higher capacity of leak compensation [16]. On the other hand, VAF, which refers to a pressure-controlled ventilation mode with a guaranteed tidal volume [17,18], does not perform comparably with PCV, while PCV has been extensively utilized in pediatric patients [19–22] because it targets volume delivery. [23–27], This is due to the fact that unlike PCV, which focuses solely on inspiratory pressure, VAF also takes into account tidal volume. Therefore, PCV should always be used while doing NIV with operating room ventilators and a standard facemask to optimize mask leak compensation.

4.2. Comparison of ventilators

The major differences among the four ventilators we tested in this study are in their maximal O_2 flow rates, peak inspiratory flow rates, and pressure generation systems (Table 1). The mask leaks were compensated for by the strong fresh gas flow of the Carestation 650, a bellow ventilator. In the Carestation 650, Vte with was not quantifiable at leak III–V, and it was poorer than any other ventilator in mask leak compensation while having the highest possible O2 flow rates at 16 L/min, higher than those of Apollo. Despite having nearly identical maximum O2 flow rates (26 L/min), Fabius Tiro and Zeus did not have similar leak compensation. When the leak was severe, the Fabius Tiro's electric piston ventilator refilled the piston entirely from the reservoir bag volume and ambient air through its negative pressure valve.

Unlike Fabius Tiro, Zeus is a turbine ventilator and works as a pressure source whose accuracy is fully dependent on the precision of the flow meter. When there is a significant mask leak, the flow meter will correctly indicate the genuine inspiratory flow rate but underestimate the expiratory tidal volume. This means that Zeus is superior to Fabius Tiro in compensating for leaks of significant size. Apollo's 150 L/min of inspiratory flow was more than double that of Fabius Tiro's 75 L/min, yet Apollo's maximum O2 flow rate of 13 L/min was just half that of Fabius Tiro's. The two platforms, Apollo and Fabius Tiro, both have separate software implementations. The two platforms, Apollo and Fabius Tiro, both have separate software implementations. These factors could account for much of the efficiency gap between the two ventilators. Since their peak inspiratory flow rates and/or maximum O2 flows are lower than those of Zeus, they are less effective at making up for leaks. When it comes to leak compensation during PCV, the Zeus is a good choice.

4.3. Comparison of O_2 flow rate

The optimal setting for all four ventilators was PCV at 10 L/min or maximal O_2 flow. The Carestation 650 ventilator's capacity to correct for leaks relied heavily on O2 flow rate, while the other three ventilators did not. Although we did not evaluate it, compensating for a leak with supplemental air flow is likely to result in a decrease in the percentage of inspiratory O2 (FiO2). However, in perioperative settings, the indication for NIV is often inadequate respiratory drive or airway collapse rather than oxygenation. If high F_iO_2 is indeed needed, NIV may not be the best solution. If effective ventilation is ensured, then a majority of patients should be able to tolerate FiO_2 below 1.0. In this study, the calculated FiO_2 was 0.71 for Zeus at maximal O_2 flow and leak level V based on an O_2 flow of 26 L/min and a total leak flow of 40.8 L/min. Clinicians need to be aware that if there is a significant circuit leak, FiO2 can drop even with maximum O2 flow and no other gas running.

4.4. Clinical relevance of leak levels

Numerous reports have detailed how air leaks occur during NIV regardless of the interface used (a facemask, a mouthpiece, or lying prone) [28–32]. Even when using the same leak setting and ventilation mode on all four ventilators, the actual leak varied. This is because different ventilators have different pressure profiles at the same setting. Unfortunately, in actual practice, leak rates with an operating room ventilator and a regular facemask during NIV are not known. In this study, we tested leaks between 0 and over 40 L/min. We opine that the range of leak levels evaluated here is clinically relevant. ICU ventilators are designed to compensate for leaks of up to 60 L/min [8].

4.5. Peak inspiratory pressure

Determining the difference between the preset PIP and the actual PIP is an alternative approach to assessing the compensation of mask leaks with PCV. We compared the preset PIP with the actual PIP at variable leak levels (Fig. 3). We found that Zeus and Apollo were able to generate actual PIP close to the preset PIP of 10 cmH_2O at low-level leaks (II and III). As the preset PIP increased, the difference between the preset and actual PIP increased. However, Zeus was the only ventilator that generated an actual PIP of 7.5 cmH_2O at the highest leak level and highest preset PIP. In clinical practice, however, Vte should be larger than what we observed at any given ventilatory setting and leak level in our trial, as preset PIP is normally less than 20 cmH_2O and patients still have some respiratory drive. Because we did not account for the patient's respiratory drive during the trial, our result may underestimate the effectiveness of NIV using an operating room ventilator and a standard mask.

5. Limitations

There are a few limitations to this study. First, it is a bench study and may not completely simulate the extent and complexity of all clinical scenarios. However, this was a well-controlled experimental setting with a wide range of leak levels that enabled us to explore the interaction between the variable leak levels and ventilatory settings commonly used with operating room ventilators. Such a study with lung models has been well-accepted [10,20,33,34]. Second, we tested only four operating room ventilators, which are manufactured by two companies. However, the software and pressure generation systems of these four ventilators are different, and two of them are equipped with VAF. Third, we tested only normal lung compliance and resistance at an I:E ratio of 1:1, while leak compensation at different ventilatory settings and lung mechanics remain to be determined. Fourth, lung mechanics were set to simulate a healthy adult. The observations from this study should not be extrapolated to pediatric patients without further study.

6. Conclusions

In this study, we found that operating room ventilators in conjunction with a regular mask provided effective NIV. However, NIV with these ventilators should be provided in PCV mode. A bellow ventilator with greater maximal O_2 flow produced better leak compensation. The optimal ventilation strategy using an operating room ventilator and a regular facemask is to use PCV with a turbine ventilator. Clinical trials are needed to validate our observations.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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Availability of data and materials

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Authors' contributions

Conception and design of the research: Shujie liu, Jinghui Shi. Acquisition of data: Shujie Liu, Ran Dong, Siyi Xiong. Analysis and interpretation of the data: Shujie Liu, Ran Dong, Siyi Xiong, Jinghui Shi. Statistical analysis: Shujie Liu, Ran Dong; Obtaining financing: Shujie Liu; Writing of the manuscript: Shujie Liu. Critical revision of the manuscript for intellectual content: Shujie Liu, Jinghui Shi. All authors read and approved the final draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations

NIV Noninvasive ventilation
PCV Pressure control ventilation
VCV Volume control ventilation
VAF AutoFlow mode
Vte Expired tidal volume
PIP Peak inspiratory pressure
ICU Intensive Care Unit
FiO2 Fraction of inspiratory O_2

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