Technical report

Evaluation of a new hyperbaric oxygen ventilator during volume-controlled ventilation

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Keywords
Airway resistance; Intensive care; Intermittent positive-pressure ventilation; Respiratory mechanics

Abstract
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Introduction: The performance of the Shangrila590 hyperbaric ventilator (Beijing Aeonmed Company, Beijing, China) was evaluated during volume-controlled ventilation.
Methods: Experiments were conducted in a multiplace hyperbaric chamber at 101, 152, 203, and 284 kPa (1.0, 1.5, 2.0 and 2.8 atmospheres absolute [atm abs]). With the ventilator in volume control ventilation (VCV) mode and connected to a test lung, comparison was made of the set tidal volume (VTset) versus delivered tidal volume (VT) and minute volume (MV) at VTset between 400 and 1,000 mL. Peak inspiratory pressure was also recorded. All measurements were made across 20 respiratory cycles.
Results: Across all ambient pressures and ventilator settings the difference between VTset and actual VT and between predicted MV and actual MV were small and clinically insignificant despite reaching statistical significance. Predictably, Ppeak increased at higher ambient pressures. With VTset 1,000 mL at 2.8 atm abs the ventilator produced significantly greater VT, MV and Ppeak.
Conclusions: This new ventilator designed for use in hyperbaric environments performs well. It provides relatively stable VT and MV during VCV with VTset from 400 mL to 800 mL at ambient pressures from 1.0 to 2.8 atm abs, as well as VTset 1,000 mL at ambient pressures from 1.0 to 2.0 atm abs.

Introduction

Hyperbaric oxygen treatment (HBOT) involves administration of 100% inspired oxygen at elevated ambient pressure. It is widely used in disorders such as acute carbon monoxide poisoning, decompression sickness, and arterial gas embolism which occasionally require intensive care.[1,2] It is a safe intervention within the common treatment pressure range 203–284 kPa (2–2.8 atmospheres absolute [atm abs]).[3] In a normobaric environment, the arterial partial pressure of oxygen (PaO_2) can only be raised by increasing the fraction of inspired oxygen (FiO_2) in a limited manner.[4] In a hyperbaric environment, the PaO_2 can be further enhanced by increasing ambient pressure and FiO_2.

Administering HBOT in ventilated intensive care unit (ICU) patients can be challenging because ordinary ICU ventilators may not work well at increased ambient pressures. Indeed, many medical devices cannot be used in hyperbaric chambers including life support technologies such as haemofiltration, electrical defibrillators and extracorporeal membrane oxygenation systems.[5,6] In recent years, a series of bench tests have been carried out on ventilators under hyperbaric conditions during basic ventilation modes, volume-controlled ventilation (VCV) and pressure-controlled ventilation (PCV).[7,8]

Pneumatical ventilators can operate safely in hyperbaric environments, but they cannot provide stable tidal volume (VT), respiratory rate (f) or minute volume (MV) without considerable user intervention.[9,10] Similarly, most electro-pneumatical ventilators cannot function well in hyperbaric chambers. In the early stage, researchers focused on empirically predicting changes in ventilation parameters under high pressures and then adjusted the parameters of the ventilator to manually compensate for the changes. With improved understanding of respiratory mechanics in hyperbaric environments, HBOT ventilators have been developed. These ventilators can automatically adjust performance when the ambient pressure changes, for example, the Siaretron 1000 Iper (Bologna, Italy).[10,11] However, these devices are expensive and not widely available in China. We tested a locally developed HBOT

ventilator to evaluate the stability of VT and MV during VCV in a hyperbaric chamber.

Methods

ETHICS APPROVAL

This study did not involve human participants, human material, or human data so ethical approval was not required.

THE VENTILATOR

The Shangrila590 ventilator is an electropneumatic ventilator from Beijing Aeonmed Company that is commonly used in the ICU in China. To comply with the safety regulations of medical hyperbaric chambers in China, the pneumatic part was placed in the chamber, and the electronic part was positioned outside the chamber (Figure 1A and B).[12,13] The two parts of the ventilator were connected through a penetrator in the chamber bulkhead, allowing doctors to operate the ventilator from outside the hyperbaric chamber. Ventilator engineers improved the control algorithm to make the ventilator work reliably and safely in a hyperbaric environment.

THE TEST LUNG

We used a Michigan Instruments PneuView®3 System (Grand Rapids, MI, USA) to measure the ventilation parameters. The detection system comprised a test lung and PneuView®3.3 software; the latter processed the test lung data which was recorded electronically.

THE CRITICAL CARE MULTIPLACE HYPERBARIC CHAMBER

Multiplace hyperbaric chambers are generally better suited for HBOT in critically ill patients than monoplace hyperbaric chambers.[14] The critical care hyperbaric chamber (GY3800-A / GY3800 M2-D) (Yantai Hongyuan Oxygen Industrial Inc., Yantai, China) is a multiplace hyperbaric chamber with an automated operation system equipped with electrocardiogram monitors, ventilators, transcutaneous oxygen and carbon dioxide tension monitors, syringe drivers, and infusion pumps to ensure continuity of treatment for ICU patients. The chambers have three compartments; two ICU chambers and a prechamber between them. These have the capacity for 24 seated people or eight gurneys.

EXPERIMENTAL CONFIGURATION

We calibrated the ventilator and the test lung at atmospheric pressure before the experiments. The test lung was located inside the hyperbaric chamber and connected to the pneumatic component of the ventilator. The digital data detected by the test lung and the ventilator were passed by penetration wires through the bulkhead to a personal computer and the electronic component of the ventilator outside the chamber (Figure 2). The ventilator was adjusted by doctors outside the chamber, and the resistance and compliance of the test lung were regulated by staff inside the chamber (Table 1). Respiratory resistance includes lung compliance and airway resistance, which needs to be matched with tidal volume to ensure safe airway pressure. Under normal physiological conditions and positive-pressure ventilation, higher compliance and lower resistance may produce larger tidal volumes, and result in stable airway pressure. So, in this study, compliance and airway resistance of the test lung were set differently between VTset

Figure 1
A – ventilator electronic component external to the chamber; B – ventilator pneumatic component inside the chamber

Figure 2
Schematic of the experimental configuration

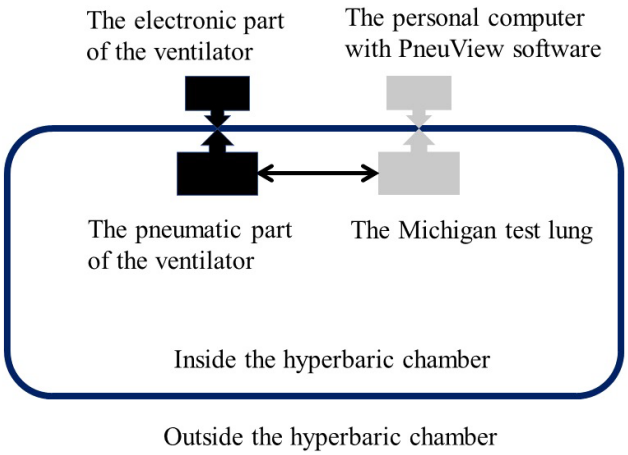


Table 1
Experimental settings for the ventilator and the test lung during volume- controlled ventilation at different ambient pressures

Ventilator settings	Volume-controlled ventilation (VCV), Respiratory rate (f) = 20 breaths per minute (BPM), Inspiratory/expiratory ratio (I/E) = 1:2, Positive end-expiratory pressure (PEEP) = 0.2 kPa, Fraction of inspired oxygen (FiO_2) = 40 %				
Ventilator VTset (mL)	400	500	600	800	1,000
Test lung compliance (mL·kPa^{-1})	200	200	200	500	500
Test lung resistance (kPa·L^{-1}·s^{-1})	2	2	2	0.5	0.5

Figure 3
A – changes in tidal volume (VT) during volume-controlled ventilation (VCV) with preset tidal volume (VTset) 400–600 mL at different ambient pressures; B – changes in tidal volume (VT) during volume-controlled ventilation (VCV) with preset tidal volume (VTset) 800–1,000 mL at different ambient pressures

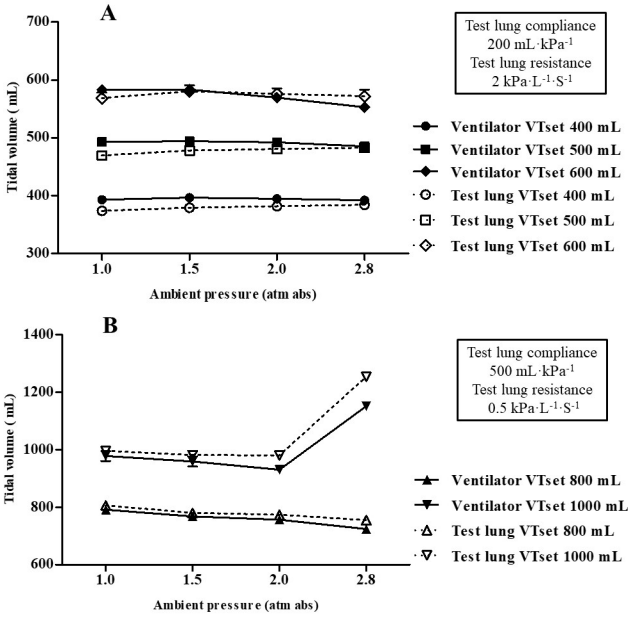
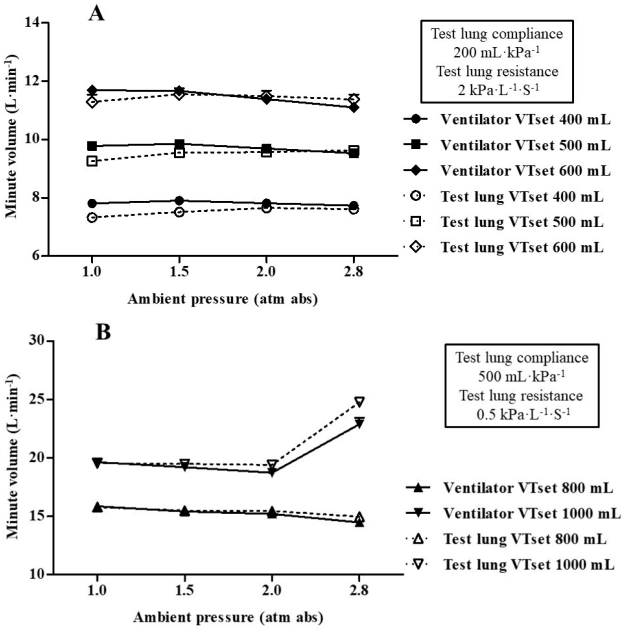


Figure 4
A – changes in minute volume (MV) during volume-controlled ventilation (VCV) with preset tidal volume (VTset) 400–600 mL at different ambient pressures; B – changes in minute volume (MV) during volume-controlled ventilation (VCV) with preset tidal volume (VTset) 800–1,000 mL at different ambient pressures



400–600 mL and VTset 800–1,000 mL according to the calibration specification in for ventilators in China.[15,16]

EXPERIMENTAL PROCEDURE

The hyperbaric chamber ambient pressure was sequentially increased from 101 kPa to 152, 203, and 284 kPa (from 1.0 to 1.5, 2.0 and 2.8 atm abs) with testing occurring at these different ambient pressures. At every pressure stage, the ventilator was operated in VCV mode at different preset tidal volumes (VTset) (400, 500, 600, 800 and 1,000 mL) and the following parameters; 20 breaths per minute (BPM), inspiratory/expiratory (I:E) ratio 1:2, positive end-expiratory pressure (PEEP) 0.2 kPa, and FiO_2 40%. The corresponding resistance and compliance of the test lung is provided in Table 1. The steady state of the ventilator after regulation was two minutes. The VT, MV, peak inspiratory pressure (Ppeak) and PEEP values were collected by the ventilator and the test lung for 20 respiratory cycles at every ambient pressure and VTset. Static lung compliance (Cs) and airway resistance (Raw) were measured by the ventilator. The temperature in the hyperbaric chamber was maintained at 24°C to 26°C.

STATISTICAL ANALYSIS

For the five values of VTset multiple factor analysis of variance was used to evaluate VT, MV, Ppeak and PEEP. The effects of the four ambient pressures and two test methods on

Table 2

Tidal volume (VT) during volume-controlled ventilation (VCV) at different ambient pressures, data are mean (standard deviation); $^{*}P < 0.05$, ventilator vs. test lung; $^{a}P < 0.05$ vs. 1.0 atm abs group, $^{b}P < 0.05$ vs. 1.5 atm abs group, $^{c}P < 0.05$ vs. 2.0 atm abs group

VTset (mL)	Equipment	VT (mL)			
		1.0 atm abs	1.5 atm abs	2.0 atm abs	2.8 atm abs
400	Ventilator	393.2 (2.4)	396.8 (2.3)^{a}	394.8 (2.3)^{a}	392.3 (3.0)^{a}
	Test lung	373.8 (3.3)*	379.3 (4.4)^{*a}	381.7 (6.1)^{*a}	384.4 (6.8)^{*a}
500	Ventilator	493.1 (3.2)	494.3 (4.7)^{a}	492.3 (2.6)^{a}	485.3 (3.8)
	Test lung	469.4 (6.0)*	478.2 (7.2)^{*a}	480.7 (6.0)^{*a}	482.9 (5.5)*
600	Ventilator	583.3 (9.2)	583.7 (8.6)	569.6 (7.8)^{b}	553.1 (7.3)^{abc}
	Test lung	568.6 (9.5)	580.5 (10.0)	576.0 (9.3)^{b}	571.9 (11.3)^{abc}
800	Ventilator	791.8 (12.9)	768.3 (12.8)^{a}	756.7 (12.5)^{ab}	724.1 (11.0)^{abc}
	Test lung	806.1 (9.2)*	780.3 (11.2)^{*a}	773.6 (9.6)^{*ab}	754.6 (11.6)^{*abc}
1,000	Ventilator	978.2 (17.3)	959.2 (17.0)^{a}	931.0 (12.9)^{ab}	1,152.0 (8.9)^{abc}
	Test lung	996.4 (13.7)*	981.6 (12.9)^{*a}	980.2 (11.8)^{*ab}	1,254.0 (7.5)^{*abc}

Table 3

Minute volume (MV) during volume-controlled ventilation (VCV) at different ambient pressures, data are mean (standard deviation); $^{*}P < 0.05$, ventilator vs. test lung; $^{a}P < 0.05$ vs. 1.0 atm abs group, $^{b}P < 0.05$ vs. 1.5 atm abs group, $^{c}P < 0.05$ vs. 2.0 atm abs group

VTset (mL)	Equipment	MV (L·min^{-1})			
		1.0 atm abs	1.5 atm abs	2.0 atm abs	2.8 atm abs
400	Ventilator	7.81 (0.02)	7.90 (0.01)^{a}	7.82 (0.01)^{a}	7.73 (0.01)^{a}
	Test lung	7.33 (0.09)*	7.51 (0.10)^{*a}	7.65 (0.08)^{*a}	7.61 (0.14)^{*a}
500	Ventilator	9.78 (0.04)	9.85 (0.11)^{a}	9.69 (0.07)^{a}	9.53 (0.06)^{b}
	Test lung	9.26 (0.14)*	9.54 (0.16)^{*a}	9.57 (0.11)^{*a}	9.63 (0.13)^{*b}
600	Ventilator	11.70 (0.05)	11.67 (0.13)^{a}	11.39 (0.08)^{b}	11.10 (0.01)^{ab}c
	Test lung	11.28 (0.25)	11.55 (0.21)^{a}	11.49 (0.19)^{b}	11.37 (0.17)^{abc}
800	Ventilator	15.86 (0.05)	15.41 (0.02)^{a}	15.20 (0.01)^{ab}	14.47 (0.05)^{abc}
	Test lung	15.79 (0.16)*	15.48 (0.23)^{*a}	15.44 (0.22)^{*ab}	14.97 (0.23)^{*abc}
1,000	Ventilator	19.63 (0.12)	19.20 (0.01)	18.73 (0.05)^{a}	22.89 (0.54)^{abc}
	Test lung	19.54 (0.33)*	19.48 (0.37)*	19.39 (0.33)^{*a}	24.77 (0.19)^{*abc}

VT, MV, Ppeak and PEEP were analysed. A *P*-value smaller than 0.05 was considered significant. We used SPSS19.0 to perform the statistical analysis and GraphPad Prism 5 to prepare graphs.

Results

At the same ambient pressure, VT and MV displayed by the ventilator and the test lung were compared. With increasing ambient pressure, the change trend at VTset 400–600 mL detected by the ventilator decreased, but the change trend detected by the test lung increased; the change trend at VTset 800–1,000 mL detected by the ventilator was in accordance with the test lung (Figures 3 and 4). There was a significant difference between the ventilator and the test lung at VTset 400–1,000 mL (Tables 2 and 3). Surprisingly, VT and MV increased sharply at VTset 1,000 mL at 2.8 atm abs.

Meanwhile, at every VTset, the Ppeak displayed by the ventilator and the test lung were almost identical at each fixed ambient pressure, except for the significant differences of Ppeak at VTset 500 mL and 800 mL at 2.0–2.8 atm abs (Table 4). However, when the ambient pressure increased, Ppeak increased obviously at VTset 400–1,000 mL (Figure 5).

Table 4

Peak inspiratory pressure (Ppeak) during volume-controlled ventilation (VCV) at different ambient pressures, data are mean (standard deviation); $^{*}P < 0.05$, ventilator vs. test lung; $^{a}P < 0.05$ vs. 1.0 atm abs group, $^{b}P < 0.05$ vs. 1.5 atm abs group, $^{c}P < 0.05$ vs. 2.0 atm abs group

VTset (mL)	Equipment	Ppeak (kPa)			
		1.0 atm abs	1.5 atm abs	2.0 atm abs	2.8 atm abs
400	Ventilator	2.44 (0.02)	2.58 (0.03)^{a}	2.71 (0.04)^{ab}	2.96 (0.05)^{abc}
	Test lung	2.47 (0.02)	2.60 (0.02)^{a}	2.73 (0.03)^{ab}	2.94 (0.04)^{abc}
500	Ventilator	3.06 (0.03)	3.28 (0.04)^{a}	3.50 (0.05)^{ab}	3.87 (0.06)^{abc}
	Test lung	3.06 (0.03)*	3.28 (0.03)^{*a}	3.48 (0.04)^{*ab}	3.78 (0.04)^{*abc}
600	Ventilator	3.67 (0.04)	4.02 (0.05)^{a}	4.24 (0.04)^{ab}	4.63 (0.05)^{abc}
	Test lung	3.68 (0.03)	4.02 (0.04)^{a}	4.23 (0.05)^{ab}	4.58 (0.07)^{abc}
800	Ventilator	2.00 (0.03)	2.04 (0.03)^{a}	2.13 (0.04)^{ab}	2.24 (0.04)^{abc}
	Test lung	2.02 (0.02)*	2.07 (0.02)^{*a}	2.16 (0.02)^{*ab}	2.25 (0.02)^{*abc}
1,000	Ventilator	2.46 (0.04)	2.59 (0.04)^{a}	2.72 (0.03)^{ab}	4.35 (0.05)^{abc}
	Test lung	2.48 (0.02)	2.61 (0.02)^{a}	2.75 (0.02)^{ab}	4.29 (0.02)^{abc}

Figure 5

A – changes in peak inspiratory pressure (Ppeak) during volume-controlled ventilation (VCV) with preset tidal volume (VTset) 400–600 mL at different ambient pressures; B – changes in peak inspiratory pressure (Ppeak) during volume-controlled ventilation (VCV) with preset tidal volume (VTset) 800–1,000 mL at different ambient pressures

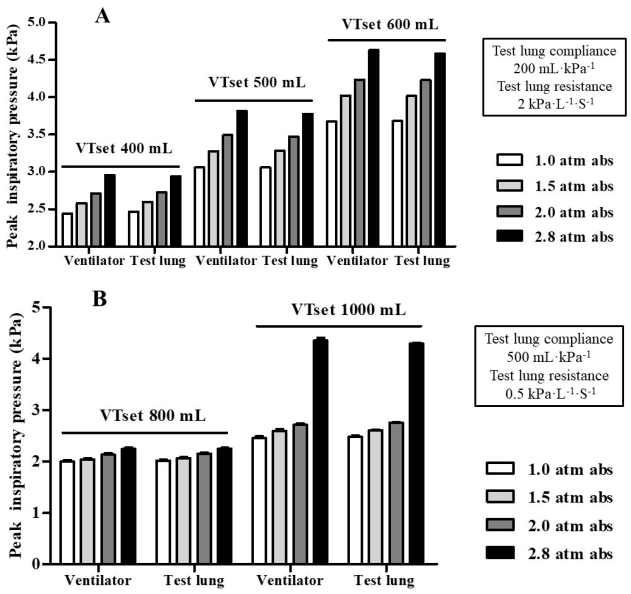
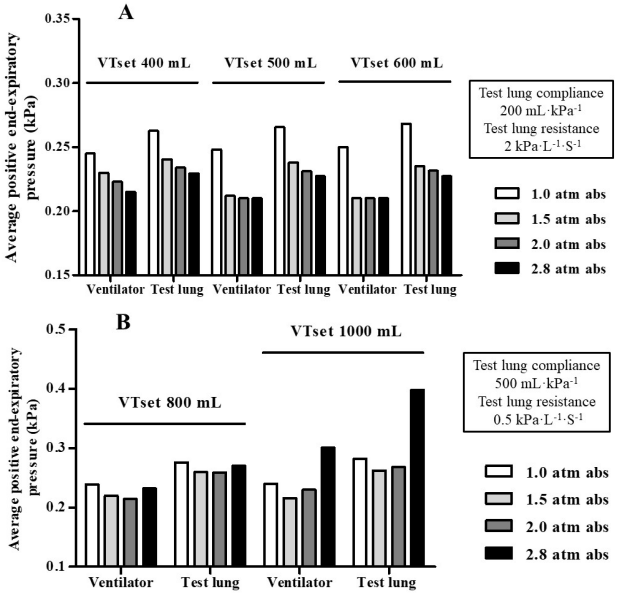


Figure 6

A – changes in positive end-expiratory pressure (PEEP) during volume-controlled ventilation (VCV) with preset tidal volume (VTset) 400–600 mL at different ambient pressures; B – changes in positive end-expiratory pressure (PEEP) during volume-controlled ventilation (VCV) with preset tidal volume (VTset) 800–1,000 mL at different ambient pressures



Positive end-expiratory pressure (PEEP) detected by the ventilator and test lung showed the same decreasing trend at VTset 400–600 mL at 1.0–2.8 atm abs (Figure 6A) and at VTset 800–1,000 mL at 1.0–2.0 atm abs. It increased only at VTset 800–1,000 mL at 2.8 atm abs (Figure 6B).

At each fixed VTset the static lung compliance (Cs) seemed to decrease as ambient pressure increased. There was a significant difference at VTset 400–1,000 mL among different ambient pressures (Table 5 and Figure 7). Airway resistance increased with increasing ambient pressure, and there was a significant difference at VTset 400–1,000 mL (Table 6 and Figure 8).

Table 5

Static lung compliance (Cs) detected by the ventilator during volume-controlled ventilation (VCV) at different ambient pressures, data are mean (standard deviation); $^{*}P < 0.05$ vs. 400 mL, $^{\#}P < 0.05$ 800 mL vs. 1,000 mL, $^{a}P < 0.05$ vs. 1.0 atm abs group, $^{b}P < 0.05$ vs. 1.5 atm abs group, $^{c}P < 0.05$ vs. 2.0 atm abs group

VTset (mL)	Static compliance (mL·kPa^{-1})			
	1.0 atm abs	1.5 atm abs	2.0 atm abs	2.8 atm abs
400	181.4 (48.8)	179.8 (35.8)	118.2 (64.1)^{ab}	83.2 (32.3)^{ab}
500	200.6 (13.7)	175.8 (38.0)	140.4 (41.1)^{ab}	107.6 (30.9)^{ab}
600	201.0 (17.1)	181.8 (35.0)	141.2 (41.8)^{ab}	127.2 (41.5)^{ab}
800	449.0 (25.7)	423.6 (106.5)	382.2 (133.3)	288.2 (85.9)^{ab}
1,000	513.8 (116.2)$^{\#}$	473.7 (123.5)$^{\#}$	484.2 (115.9)$^{\#}$	373.5 (113.0)^{ab}

Table 6

Airway resistance (Raw) detected by the ventilator during volume-controlled ventilation (VCV) at different ambient pressures, data are mean (standard deviation); $^{*}P < 0.05$ vs. 400 mL, $^{\Delta}P < 0.05$ vs. 500 mL, $^{\#}P < 0.05$ 800 mL vs. 1,000 mL, $^{a}P < 0.05$ vs. 1.0 atm abs group, $^{b}P < 0.05$ vs. 1.5 atm abs group, $^{c}P < 0.05$ vs. 2.0 atm abs group

VTset (mL)	Airway resistance (kPa·L^{-1}·S^{-1})			
	1.0 atm abs	1.5 atm abs	2.0 atm abs	2.8 atm abs
400	0.29 (0.07)	0.45 (0.10)	0.51 (0.04)^{a}	0.62 (0.16)^{ab}
500	0.53 (0.03)*	0.61 (0.18)*	0.66 (0.16)^{*a}	0.83(0.36)^{*ab}
600	0.67 (0.07)$^{*\Delta}$	0.69 (0.05)$^{*\Delta}$	1.05 (0.18)$^{*\Delta a}$	1.31 (0.30)$^{\Delta ab}$
800	0.22 (0.05)	0.27 (0.04)	0.28 (0.04)	0.39 (0.08)^{abc}
1,000	0.27 (0.05)$^{\#}$	0.35 (0.03)$^{\#}$	0.32(0.11)$^{\#}$	0.70 (0.20)$^{\#abc}$

Figure 7

Changes in static lung compliance (Cs) detected by the ventilator during volume-controlled ventilation (VCV) at different ambient pressure; error bars represent standard deviation

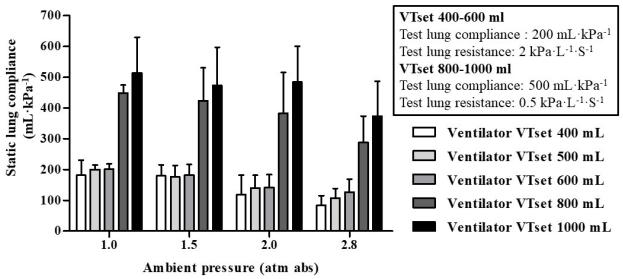
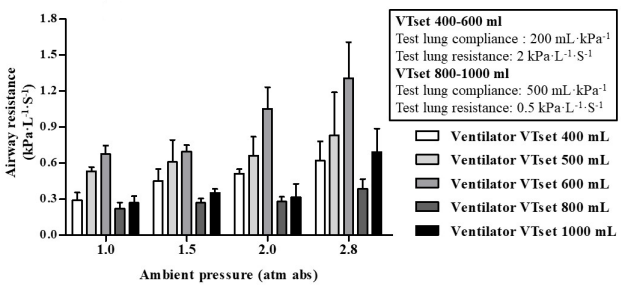


Figure 8

Changes in airway resistance (Raw) detected by the ventilator during volume-controlled ventilation (VCV) at different ambient pressures; error bars represent standard deviation



Interestingly, it was observed that inspiratory flow increased suddenly at VTset 1,000 mL at 2.8 atm abs, associated with increased VT, MV and Ppeak. The flow setting was a square wave in the ventilator setting. Therefore, the flow displayed by the ventilator was approximately equal to the maximum inspiratory flow measured by the test lung. Inspiratory time (Ti) and I:E ratio will affect inspiratory flow at a fixed VTset. When the theoretical inspiratory flow was less than 60 L·min^{-1}, the inspiratory flow detected by the ventilator and test lung was stable and near the theoretical value. When the theoretical inspiratory flow was more than 60 L·min^{-1}, inspiratory flow measured by the ventilator decreased between 1.0 to 2.8 atm abs, but when measured by the test lung, it increased (Table 7).

Discussion

Previous research has shown that ordinary ventilators normally used at atmospheric pressure cannot maintain a stable VT during VCV when operated at higher pressures.

Table 7
Inspiratory flow measured by the ventilator and the test lung at different respiratory rates and inspiratory:expiratory (I:E) ratios; atm abs – atmospheres absolute; Ti – inspiratory time

Breaths per min	Inspiratory time (I:E ratio)	Theoretical value of inspiratory flow (L·min^{-1})	Ventilator / Test lung Maximum inspiratory flow (L·min^{-1})	
			1.0 atm abs	2.8 atm abs
10	Ti = 1.0 s (1:5)	60.0	61.0 / 147.2	53.0 / 209.7
	Ti = 1.5 s (1:3)	40.0	50.8 / 33.0	40.0 / 41.0
	Ti = 2.0 s (1:2)	30.0	30.0 / 32.3	30.0 / 38.5
15	Ti = 1.0 s (1:3)	60.0	60.0 / 138.5	60.0 / 190.9
	Ti = 1.3 s (1:2)	46.2	45.0 / 50.0	46.0 / 46.5
20	Ti = 0.8 s (1:2.8)	75.0	72.0 / 79.1	52.0 / 84.1
	Ti = 0.9 s (1:2.3)	66.7	65.0 / 94.1	52.0 / 96.6
	Ti = 1.0 s (1:2)	60.0	60.0 / 148.7	51.0 / 218.8
	Ti = 1.2 s (1:1.5)	50.0	50.0 / 57.5	60.0 / 56.1

Inspiratory flow provided by the ventilator will decrease with increasing ambient pressure.[7–11] The reason is that during HBOT the respired gas density becomes higher and produces more turbulent flow in airways and external circuits.[17] To obtain stable inspiratory flow, more driving pressure (△P) must be provided by the ventilator to overcome the increased Raw produced by the increased turbulent flow.[11] To maintain stable VT a ventilator used in the hyperbaric chamber must autoregulate △P to compensate for this change.

EVALUATION OF VT DURING VCV AT HIGH AMBIENT PRESSURE

During VCV, the Shangrila590 ventilator can achieve constant VT and MV, even though VT and MV decreased within a narrow range compared with VTset, except at VTset 1,000 mL at 2.8 atm abs. Measured by the test lung, the range of VT was less than 5% for VTset of 400–800 mL from 1.0 to 2.8 atm abs. The range of VT was 2–5% for VTset 1,000 mL from 1.0 to 2.0 atm abs. In contrast, in non-adapted ICU ventilators during VCV in hyperbaric environments the fall in VT at the same ambient pressures was greater than 50%.[7,9] The Siaretron IPER 1000 hyperbaric ventilator is CE-certified for hyperbaric use in Europe. In tests of this device during VCV (Ti 1.0 s), a 4–10% increase in VT at VTset 500 mL at ambient pressures between 2.2–2.8 atm abs and an 11–21% decrease at VTset 750 mL at ambient pressures between 2.0–2.8 atm abs was seen.[10] A modified Penlon Nuffield 200 used in a monoplace hyperbaric chamber and fixed outside the chamber showed a 40% decrease in VT at ambient pressures from 1.0 to 2.3 atm abs (flow setting: 0.25–1 L·s^{-1}).[18]

In the present study, we were surprised to find that VT and MV increased by 27% at 2.8 atm abs with VTset at 1,000 mL, and we carried out complementary tests (Table 7). The relationship between inspiratory valve opening and volume flow is constant only for a specified gas density.[7] When the theoretical inspiratory flow is more than 60 L·min^{-1}, the inspiratory flow provided by the ventilator is unstable. If the inspiratory valve cannot close immediately at the end of inspiration, more inspiratory flow will be detected by the test lung. The opening degree and closing speed of the ventilator valve may be influenced by the high inspiratory flow, especially at high pressure.

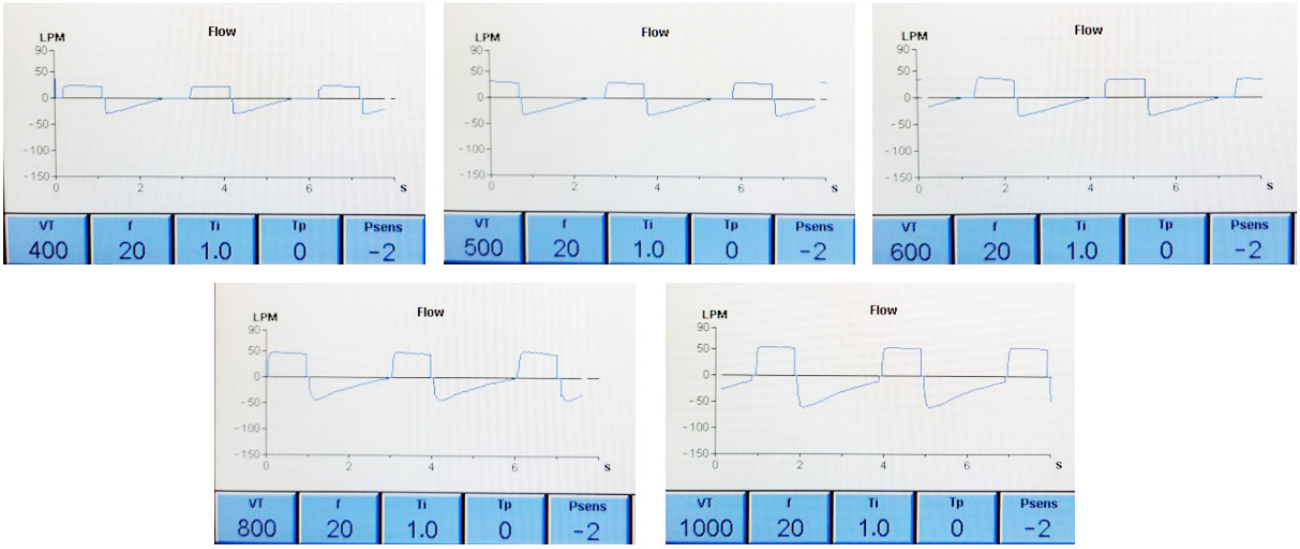
CHANGES IN Ppeak DURING VCV AT HIGH AMBIENT PRESSURE DUE TO HIGHER INSPIRATORY RESISTANCE

Peak inspiratory pressure primarily reflects inspiratory resistance and △P indirectly, as our results show in Table 4 and Figure 5. In clinical use, attention must be given to Ppeak increases associated with increases in ambient pressure. These increases cannot be avoided, though some patient-centered strategies may help such as ensuring adequate paralysis, sputum aspiration, bronchodilation (if applicable). Similarly, environmental factors such as reducing ambient pressure and use of lower density respired gases (such as a helium oxygen mixture) can help if the clinical circumstances allow it.

CHANGES IN PEEP DURING VCV AT HIGH AMBIENT PRESSURE BECAUSE OF HIGHER EXPIRATORY RESISTANCE

Higher expiratory resistance may occur, and expiratory flow may decrease during HBO.[17] In a previous study, PEEP was set to 0.1–0.2 kPa in an ICU ventilator (EVITA 4), and PEEP decreased to zero at 1.9 and 2.8 atm abs.[7] The valve that regulates the PEEP is controlled pneumatically by the ventilator and is likely to be affected by the higher density of driving gas.[7] As shown in Figure 6, the PEEP at VTset 400–1,000 mL decreased with increasing

Figure 9
Flow-time curve displayed by the ventilator during volume-controlled ventilation (VCV) with preset tidal volume (VTset) 400–1,000 mL at 2.8 atm abs



ambient pressure, but at 2.8 atm abs, the PEEP at VTset 800–1,000 mL increased. Figure 9 shows that at 2.8 atm abs, the expiratory flow at VTset 400–600 mL returned to zero (baseline) and remained static until the next inspiration; the expiratory flow at VTset 800 mL returned to baseline without any buffer time, which resulted in a slight increase in PEEP; the expiratory flow at VTset 1,000 mL did not return to baseline before the next inspiration; and incomplete expiration resulted in an obvious increase in PEEP.

CHANGES IN Cs AND Raw DURING VCV AT HIGH AMBIENT PRESSURE

Volume control ventilation emphasises stable volume flow, but at higher ambient pressure, the stability of volume flow accompanies the increased mass flow because of increased gas density. According to the resistance formula, Cs and Raw can directly influence the work of breathing.[19] Combined with the breathing equipment itself, the work of breathing will be increased compared with that in a normobaric environment.[6,19] In the ICU, the endotracheal tube diameter is a critical factor in breathing work.[20] Additionally, we can decrease airway resistance by appropriately prolonging the inspiratory time, using a helium oxygen mixture to decrease the gas density, or down regulating ambient pressure.[19]

LIMITATIONS

A limitation of this research is the narrow VTset levels of 400–1,000 mL, and small VTset volumes relevant to paediatric practice were not included in this work. We will conduct additional research using a small VTset of 50–300 mL in the future to comprehensively check the performance of the ventilator in a hyperbaric chamber.

Conclusions

In summary, over a range of ambient pressures from 1.0 to 2.8 atm abs, the new hyperbaric oxygen ventilator (Shangrila590) made in China can provide relatively stable VT and MV during VCV with VTset levels from 400 to 1,000 mL, except at VTset 1,000 mL at 2.8 atm abs. The changes in VT are acceptable with VTset from 400 to 800 mL at 1.0–2.8 atm abs and 1,000 mL at 1.0–2.0 atm abs. During VCV, Ppeak unavoidably increases, and PEEP may be influenced at high ambient pressure.

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