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

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

Abstract
(Wang C, Yu Q, Liu Y, Ren Z, Liu Y, Xue L. Evaluation of a new hyperbaric oxygen ventilator during pressure-controlled ventilation. Diving and Hyperbaric Medicine. 2024 30 September;54(3):212–216. doi: 10.28920/dhm54.3.212-216. PMID: 39288926.)
Introduction: The stability of a new hyperbaric ventilator (Shangrila590, Beijing Aeonmed Company, Beijing, China) at different clinically relevant pressures in a hyperbaric chamber during pressure-controlled ventilation (PCV) was investigated.
Methods: The ventilator was connected to a test lung in the multiplace hyperbaric chamber. The inspiratory pressure (PI) of the ventilator was set to 1.0, 1.5, 2.0, 2.5 and 3.0 kPa (approximately 10, 15, 20, 25 and 30 cmH_2O). The compliance and resistance of the test lung were set to 200 $mL \cdot kPa^{-1}$ and 2 $kPa \cdot L^{-1} \cdot s^{-1}$, respectively. Experiments were conducted at 101, 203 and 284 kPa ambient pressure (1.0, 2.0 and 2.8 atmospheres absolute respectively). At each of the 5 PI values, the tidal volume (VT), peak inspiratory pressure (Ppeak) and peak inspiratory flow (Fpeak) displayed by the ventilator and the test lung were recorded for 20 cycles. Test lung data were considered the actual ventilation values. The ventilation data were compared among the three groups to evaluate the stability of the ventilator.
Results: At every PI, the Ppeak detected by the ventilator decreased slightly with increasing ambient pressure. The Fpeak values measured by the test lung decreased substantially as the ambient pressure increased. Nevertheless, the reduction in VT at 284 kPa and PI 30 cmH_2O (compared to performance at 101 kPa) was comparatively small (approximately 60 ml).
Conclusions: In PCV mode this ventilator provided relatively stable VT across clinically relevant PI values to ambient pressures as high as 284 kPa. However, because Fpeak decreases at higher ambient pressure, some user adjustment might be necessary for precise VT maintenance during clinical use at higher PIs and ambient pressures.

Introduction

Hyperbaric oxygen treatment (HBOT) is widely used for patients in the intensive care unit (ICU) for conditions such as acute carbon monoxide poisoning, decompression sickness, and arterial gas embolism.[1–3] Most life support technologies, such as haemofiltration, electrical defibrillation and extracorporeal membrane oxygenation, are incompatible with hyperbaric environments, but ventilators are a necessary exception.[4,5] However, standard ICU ventilators cannot maintain stable output during HBOT, especially when operating with volume-controlled ventilation (VCV). Tests have been carried out on ventilators in hyperbaric environments with basic ventilation modes, such as VCV and pressure-controlled ventilation (PCV).[6–10] Early use of standard ICU ventilators for HBOT required manual adjustment to compensate for predicted changes. According to the equation:[11] $\sqrt{\Delta P} \propto flow \times density$, if gas density doubles, maintaining a stable ventilator driving pressure (ΔP) will result in reducing flow to half; however, obtaining stable flow needs four times ΔP. Thus, PCV is preferentially used with better stability than VCV.[7,11]

In the last few years, hyperbaric ventilators have been developed, replacing the standard ICU ventilators in hyperbaric chambers. These incorporate automatic pressure compensation systems.[11] For example, the Siaretron 1000 IPER ventilator (Bologna, Italy) can maintain a constant tidal volume (VT) with VCV at various ambient pressures by adjusting the inspiratory valve opening within the operational range, but it does not meet the hyperbaric chamber safety requirements of China.[8,12,13] Recently, bench tests of a new hyperbaric ventilator made in China (Shangrila590, Beijing Aeonmed Company, China) were carried out in our hospital. The Shangrila590 ventilator was evaluated in VCV mode in a 101–284 kPa (1.0–2.8 atmospheres absolute [atm abs]) environment.[14] In the present study, the peak inspiratory pressure (Ppeak) and VT stability of the Shangrila590 were measured during PCV in a hyperbaric chamber.

Methods

VENTILATOR

The Shangrila590 ventilator is an electropneumatic ventilator manufactured by the Beijing Aeonmed Company in China. According to the safety regulations of medical hyperbaric chambers in China, the pneumatic part of the ventilator is situated within the chamber, and the electronic component is outside the chamber.[12,13] These two components were connected through a chamber wall penetrator. In the experiment, doctors operated the ventilator outside the hyperbaric chamber.

TEST LUNG

A Michigan Instruments PneuView® 3 System (Grand Rapids, MI, USA) was used to measure the ventilation parameters. The detection system included a test lung and PneuView® 3.3 software. The test lung data were collected and recorded by a computer with PneuView® 3.3 software.

CRITICAL CARE MULTIPLACE HYPERBARIC CHAMBER

The critical care hyperbaric chamber (GY3800-A [GY3800 M2-D], Yantai Hongyuan Oxygen Industrial Inc., Yantai, China) is a multiplace hyperbaric chamber that has the capacity for 24 seated people or eight gurneys. In addition to ventilators, electrocardiogram monitors, transcutaneous oxygen (O_2) and carbon dioxide (CO_2) tension monitors, syringe drivers, and infusion pumps were equipped to ensure the continuous treatment of ICU patients.

EXPERIMENTAL CONFIGURATION

The ventilator and the test lung were calibrated at atmospheric pressure before the experiments. The test lung was located inside the hyperbaric chamber and connected to the pneumatic part of the ventilator. The ventilation data were detected by the test lung and recorded by a computer. Moreover, the ventilation data were detected by the ventilator and displayed on the screen of the ventilator component. According to the parameters shown in the 'Calibration Specification for Ventilators in China', the parameters of the ventilator and test lung were set by the investigators.[15,16]

EXPERIMENTAL PROCEDURE

Tests were undertaken at three hyperbaric chamber pressures: 101, 203 and 284 kPa (1.0, 2.0 and 2.8 kPa (1.0, 2.0 and 2.8 atm abs). Under each ambient pressure, the ventilator was operated in PCV mode at five preset inspiratory pressure (PI) values being 1.0, 1.5, 2.0, 2.5 and 3.0 kPa (approximately 10, 15, 20, 25 and 30 cmH_2O). Since ventilation pressures in the clinical setting are commonly expressed in cmH_2O we use that metric in reporting VT results. Other PCV parameters were the respiratory rate (f) at 15 breaths per minute (BPM), inspiratory/expiratory ratio (I/E) at 1:2, positive end-expiratory pressure (PEEP) at 0 kPa, and fraction of inspired oxygen (FiO_2) 40%.[15,16] The resistance and compliance of the test lung were set at 200 $mL{\cdot}kPa^{-1}$ and 2 $kPa{\cdot}L^{-1}{\cdot}s^{-1}$, respectively.[15,16] The ventilator was considered at steady state two minutes after setting changes. The Ppeak and VT data measured by the ventilator and test lung were collected for 20 cycles in each setting ($n = 20$). Outcomes for these measures are expressed as the means and standard deviations of those 20 readings. Peak inspiratory flow (Fpeak) could only be detected by the test lung in each setting. The temperature in the hyperbaric chamber was maintained between 24°C and 26°C.

Results

EFFECTS OF DIFFERENT AMBIENT PRESSURES ON Ppeak AND Fpeak DURING PCV

When the ambient pressure increased, the Ppeak detected by the ventilator decreased slightly at every PI setting (Table 1). Compared with the Ppeak at 1.0 atm abs, the decrease in this value was less than 5% at 2.0 atm abs, and it was 8–10% at 2.8 atm abs. Inspiratory flow provided by

Table 1
Value of peak inspiratory pressure (Ppeak) during pressure-controlled ventilation (PCV) at different ambient pressures; data are mean (standard deviation)

Inspiratory pressure kPa (cmH_2O)	Peak pressure detected by the ventilator (kPa)		
	101 kPa (1 atm abs)	**203 kPa (2 atm abs)**	**284 kPa (2.8 atm abs)**
1.0 (10)	1.15 (0.03)	1.20 (0.05)	1.10 (0.03)
1.5 (15)	1.72 (0.03)	1.72 (0.03)	1.62 (0.04)
2.0 (20)	2.39 (0.09)	2.37 (0.07)	2.18 (0.10)
2.5 (25)	2.95 (0.06)	2.87 (0.07)	2.75 (0.45)
3.0 (30)	3.43 (0.06)	3.32 (0.08)	3.18 (0.05)

Figure 1
Mean peak inspiratory flow (Fpeak) measured by the test lung during pressure-controlled ventilation at different ambient pressures and at five levels of inspiratory pressure (PI); error bars are standard deviation; atm abs – atmospheres absolute

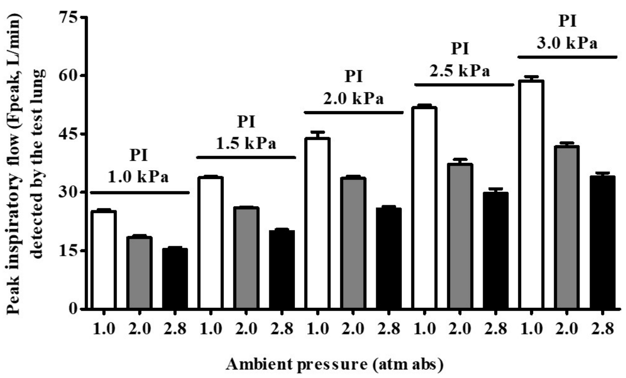
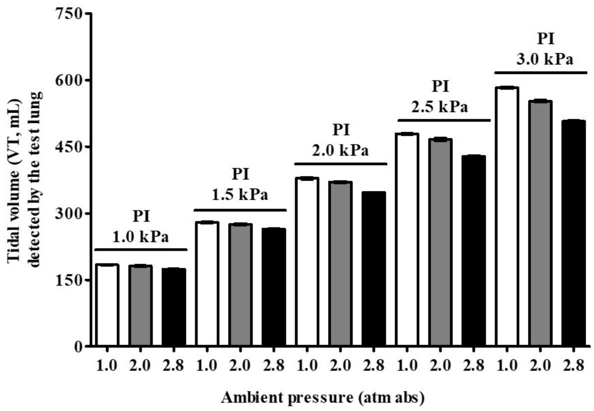


Figure 2
Mean tidal volume (VT) measured by the test lung during pressure-controlled ventilation at different ambient pressures and at five levels of inspiratory pressure (PI); error bars are standard deviation; atm abs – atmospheres absolute



the ventilator during PCV was evaluated by Fpeak, which was detected only by the test lung. Figure 1 shows that with a fixed respiratory system, Fpeak decreased significantly as the ambient pressure increased at every PI value. The Fpeak decreased by 26% at 2.0 atm abs and 41% at 2.8 atm abs compared with that at 1.0 atm abs.

EFFECTS OF DIFFERENT AMBIENT PRESSURES ON VT DURING PCV

When the ambient pressure increased, the VT detected by the test lung decreased slightly at every PI setting (Figure 2). Compared with the VT at 1.0 atm abs, at a low PI (1.0–2.0 kPa), the VT decrease was less than 2% at 2.0 atm abs and 8% at 2.8 atm abs; at a high PI (2.5–3.0 kPa), the VT decrease was 3–5% at 2.0 atm abs and 10–13% at 2.8 atm abs.

Discussion

Essentially, a ventilator is a generator of gas flow in a mechanical ventilation system.[11] Various ventilation modes have emerged which determine how a ventilator controls the gas flow to produce effective pulmonary ventilation. Regardless of the complexity of ventilation modes, they are different combinations of basic models, such as PCV, VCV and spontaneous (SPONT) ventilation.[7–9] In terms of flow generation and control, ventilation during HBOT introduces added complexity and has been investigated by many researchers.

Gas flow occurs between the supply pressure of the ventilator (Pv) and the internal pressure inside the respiratory system of the patient (Pp) which is approximately equal to the environmental pressure (Pe). The driving pressure (ΔP) of flow generation is defined as the difference between Pv and Pp (or Pe), and ΔP is the direct power of flow generation.[11,17] During HBOT, Pe is no longer a constant but rather a variable. Pe increases and causes a decrease in ΔP, leading to the unstable output of standard ICU ventilators.[7,8,11] The ΔP change induced by the ambient pressure is one factor that determines whether gas flow can be generated; the other factor is the flow type. Compared with laminar flow, achieving the same flow under turbulent conditions needs more ΔP; moreover, during HBOT, in the same respiratory system, the prevalence of turbulent flow increases because of the high gas density.[17] Theoretically, with increasing ambient pressure, obtaining stable pressure requires reducing gas flow; in contrast, obtaining stable gas flow requires increasing pressure. The improved algorithm of the hyperbaric ventilator automatically controls gas flow to compensate for these changes caused by increased ambient pressure while maintaining stable output.[6–11]

Pressure controlled ventilation aims to provide constant airway pressure during inhalation. Table 1 shows a roughly stable Ppeak with increasing ambient pressure. The Shangrila590 can maintain a stable Ppeak by decreasing Fpeak with increasing ambient pressure (Figure 1). Others have shown that the time to reach the preset PI decreases because of high airway resistance at high ambient pressure, although Ppeak can reach the preset PI value.[7]

Physiologically, VT may vary between breaths with PCV because of uncertain respiratory resistance, but it is independent of ambient pressure. However, if the respiratory system is stable and ambient pressure is fixed, VT will remain stable. With increasing ambient pressure, the airway resistance increases, and Fpeak decreases to obtain a stable Ppeak (Figure 1). If the inspiratory time (Ti) is sufficient, VT is stable; if Ti is insufficient, VT obviously decreases.[7] In our study, although Fpeak decreases, at a lower PIs (1.0–2.5 kPa [10–25 cmH_2O]), VT is roughly stable; at a high PI (2.5–3.0 kPa [25–30 cmH_2O]), VT decreases by 10–13% at 284 kPa (2.8 atm abs) (Figure 2). In practice, on the one hand, if the respiratory rate increases or Ti decreases, a decrease in Fpeak induces a decrease in VT even in patients with stable conditions. On the other hand, if the increase in airway resistance is further induced by disease progression, the decrease in Fpeak is amplified, and VT eventually decreases. Therefore, during use of a ventilator in hyperbaric conditions we must carefully monitor VT, carry out percutaneous O_2 and CO_2 monitoring and properly regulate Ti to avoid incomplete inhalation during use of PCV mode.

LIMITATIONS

First, the test lung accuracy was not calibrated at high ambient pressures. In the clinic and in HBOT, a ventilator operates continuously as the setting parameters are regulated. The test lung and the ventilator were all calibrated at normal atmospheric pressures before the experiments. In the pre-experiment phase, a water tank was used as a simulated lung to determine the accuracy of the ventilator spirometer at high ambient pressures. The water tank could detect the TV of the ventilator at different ambient pressures according to the change in the water level roughly and continuously. The VT values of the ventilator and the water tank data were similar. However, this water tank could not be used in the experiments because of its low precision (50 mL).

Second, humidification was not used. To avoid the accumulation of a large amount of condensed water in the test lung, humidification was not used in the experimental system. In China, according to National Standards, humidifiers with high voltages (> 24 V) could not be used in hyperbaric chambers. Additionally, it is indeed a fact that humidification will add airway resistance.[19,20]

Conclusions

In summary, with increasing ambient pressure from 101–284 kPa (1.0–2.8 atm abs), the Shangrila590 ventilator provided an approximately stable Ppeak value during PCV with an PI ranging from 1.0 to 3.0 kPa (10–30 cmH_2O). However, a stable Ppeak was accompanied by a decrease in Fpeak as the ambient pressure increased, and incomplete inhalation could occur if inspiratory time is inadequate.

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Conflicts of interest and funding: nil

Submitted: 15 March 2024
Accepted after revision: 18 May 2024