Evaluation and Characteristic of Modified Ventilator Under Hyperbaric Conditions During Volume-controlled Ventilation

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Abstract

Purpose The stability of the modified ventilator (Shangrila590, Beijing Aeonmed Company, Beijing, China) was evaluated under hyperbaric conditions during volume-controlled ventilation in this study by Michigan test lung (5601i, Grand Rapids, MI, US).

Methods Experiments were performed inside the multiplace hyperbaric chamber at 1.0, 1.5 and 2.0 atmospheres absolute (ATA). The modified ventilator placed inside the hyperbaric chamber was connected to the test lung. During volume-controlled ventilation (VCV), data for the test lung were collected by a personal computer outside the hyperbaric chamber. The preset tidal volume (V_{Tset}) of the ventilator (400-1000 ml) and the resistance and compliance of the testing lung were adjusted before the experiments at every ambient pressure. With every test setting, the tidal volume (V_T), inspiratory airway peak pressure (P_{peak}) and minute volume (MV) displayed by the ventilator and the test lung were recorded by the computer. We compared the ventilator and test lung data under 1.0, 1.5 and 2.0 ATA to evaluate the stability of the modified ventilator.

Results The variation in V_T in the test lung and the ventilator at different ambient pressures changed within a narrow range, and the differences were statistically significant. In every test setting, changes in the MV of the ventilator were limited and acceptable, with significant differences at different ambient pressures. However, P_{peak} increased obviously, as detected by the ventilator and test lung at higher ambient pressure during VCV.

Conclusions The modified Shangrila590 ventilator can work well in a hyperbaric chamber. It can provide relatively stable V_T and MV during VCV with V_{Tset} from 400 ml to 1000 ml when the ambient pressure increases from 1.0 ATA to 2.0 ATA. The raised ambient pressure will lead to increased gas density, which may result in more airway resistance and higher P_{peak} during VCV.

Key Messages

The modified ventilator can work well with stable V_T and MV during VCV in hyperbaric condition. P_{peak} increased obviously because of the raised airway resistance due to high ambient pressure.

Introduction

Hyperbaric oxygen (HBO) therapy involves treatment with a high fraction of inspired oxygen (FiO_2) at higher than atmospheric pressure, whereby increased pressures depend on guidelines and indications. HBO therapy is widely used in critically ill patients in the intensive care unit (ICU), such as for acute carbon monoxide poisoning, decompression sickness, arterial gas embolism, radiation-induced tissue injury, and acute traumatic ischemic injury [1,2]. HBO therapy remains among the safest therapies used today under the common range of the 2-3ATA environment [3]. Arterial partial pressure of oxygen (PaO_2) can be improved through increased pressure of oxygen (PO_2) in inspired breathing gas physiologically,

especially during HBO treatment. According to the gas law, PO_2 in inspired breathing gas can be elevated not only by increasing FiO_2 but also by increasing the pressure of breathing gas. Under a normal baric environment, we can only limitedly raise PO_2 by increasing FiO_2 [4]. Alternatively, we can elevate PO_2 by increasing ambient pressure and FiO_2 , which can raise the oxygenated efficiency of pulmonary tissue in the hyperbaric chamber. When the ventilator is placed in the hyperbaric chamber with the same parameters as outside the chamber, pulmonary gas exchange will be markedly improved if mechanical ventilation can provide stable pulmonary ventilation. However, the ordinary ventilator used in the ICU does not work well during HBO therapy because of the high ambient pressure. This limits mechanical ventilation carried out during HBO therapy. Overall, broadening the field of mechanical ventilation may benefit patients on mechanical ventilation who need HBO therapy.

Not all medical devices can be subjected to hyperbaric chambers; indeed, most life support technologies, such as hemofiltration, electrical defibrillation and extracorporeal membrane oxygenation, are at present incompatible with the hyperbaric environment [5,6].

Pneumatical ventilators can operate in hyperbaric environments safely, but they cannot provide stable V_T , respiratory rate (RR) or MV with raised ambient pressure [7,8]. Stable operation of a ventilator should be the guarantor for patients on mechanical ventilation, not only in the ICU but also in the hyperbaric chamber. Modern ventilators tend to be electropneumatical and electronic. In recent years, a series of bench tests have been carried out on ventilators under hyperbaric conditions during different ventilation models, such as VCV and pressure-controlled ventilation (PCV) [9,10]. Nevertheless, most electropneumatical ventilators cannot function well in hyperbaric chambers. In the early stage, researchers focused on empirically predicting changes in ventilation parameters under specific high pressures and then adjusted the parameters of the ventilator to manually compensate for the changes. With the understanding of respiratory mechanics in hyperbaric environments and the development of modern ventilator technology, modified ventilators for hyperbaric conditions have been developed. Modified ventilators can adjust the compensation by itself automatically, precisely and rapidly when ambient pressure changes, for example, Siaretron 1000 lper (Bologna, Italy) [10,11]. However, the type of ventilator for hyperbaric conditions is limited globally. In China, we do not have our own ventilator for hyperbaric conditions with independent intellectual property rights. In brief, we first modified the Shangrila590 ventilator (Beijing, China) and then performed a series of bench tests in a hyperbaric chamber before putting it to use clinically. In this study, we detected the stability of V_T and MV by a test lung during VCV in a hyperbaric chamber, and we clarified the characteristics of hyperbaric ventilation according to the respiratory mechanics parameters.

Methods

The ventilator

The Shangrila590 ventilator is an electropneumatic ventilator from Beijing Aeonmed Company that is commonly used in the ICU in China. According to the safety regulations of medical hyperbaric chambers

in China [12,13], the pneumatic part was placed in the chamber, and the electronic part was assembled out of the chamber. The two parts of the ventilator were connected with wire through the chamber without leakage, allowing doctors to operate the ventilator outside the hyperbaric chamber. Ventilator engineers modified the algorithm and replaced some components of the ordinary ventilator to make the ventilator work reliably and safely in a hyperbaric environment.

The test lung

We used the Model 5601i Adult/Infant PneuView System (Michigan Instrument, Grand Rapids, MI, US) to detect ventilation parameters. The detection system contains Michigan test lung and PneuView data collection software. Model 5601i houses an electronic interface module, which converts the pressure signal from the test lung to digital data and transfers these data to a personal computer. PneuView data collection software serves as the link between the test lung and the computer.

The critical care multiplace hyperbaric chamber

It has been proven that a multiplace hyperbaric chamber is better suited for HBO treatment of critically ill patients than a monoplace hyperbaric chamber because it permits appropriate ICU equipment to be used inside the chamber by staff [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 (O_2) and carbon dioxide (CO_2) tension monitors, syringe drivers, and infusion pumps, among others, to ensure the continuous treatment of ICU patients. Our chambers have three compartments, two ICU chambers and a prechamber between them, and have the capacity for 24 seated people or 8 gurneys.

The 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 part of the ventilator. The digital data detected by the test lung were passed by electrical penetration and wires through the bulkhead to the personal computer outside (Figure 1). According to the parameters shown in the Calibration Specification for Ventilators [15], the ventilator was adjusted by the doctors outside, and the resistance and compliance of the test lung were regulated by the staff inside according to the test settings in Table 1.

Experimental procedure

The hyperbaric chamber pressure rose sequentially to 1.0 ATA, 1.5 ATA and 2.0 ATA. At every pressure stage, the ventilator was operated in different V_{Tset} (400-1000 ml), f 20 BPM, I/E 1:2, PEEP 2 cmH₂O, FiO₂ 40 %), with the corresponding resistance and compliance of the test lung provided in Table 1. The steady state of the ventilator after regulation was 2 minutes. Data were collected by the software for 20 cycles at

every setting. The temperature in the hyperbaric chamber was maintained at a steady temperature of 25 °C to 26 °C.

Statistical analysis

Multiple analyses of variance were used to evaluate the impact of the ventilator and the test lung, different ambient pressure conditions, and different V_{Tset} (400-1000 ml)

of VCV. Post hoc comparisons were performed for multiple comparisons when Mauchly's test of sphericity showed significance. A p value smaller than 0.05 was considered significant. We used SPSS 19.0 to perform the statistical analysis and GraphPad Prism 5 to prepare graphs.

Results

During VCV with every V_{Tset} , V_T displayed by the ventilator itself was higher than that detected by the test lung in the same ambient pressure, especially for the V_{Tset} 800 ml groups and V_{Tset} 1000 ml groups (Table 2). With increased ambient pressure, V_T decreased not only in the test lung groups but also in the ventilator groups. Changes in V_T in the test lung and ventilator at different ambient pressures seemed stable, and the differences were statistically significant (Figure 2). Compared with V_{Tset} , downtrends of V_T displayed by the ventilator were 0.5-1 % for the V_{Tset} 400 ml group, 1-2.6 % for the V_{Tset} 500 ml group, 4-6.5 % for the V_{Tset} 600 ml group, 5-8 % for the V_{Tset} 800 ml group and 4.7-7.1 % for the V_{Tset} 1000 ml group when the ambient pressure increased from 1.0 ATA to 2.0 ATA. Meanwhile, we evaluated the MV displayed by the ventilator during VCV at different ambient pressures (Figure 3). At every V_{Tset} , changes in MV were limited to the range 1.0-2.0 ATA, and there were significant differences at different ambient pressures (Table 3).

With increased ambient pressure during VCV at a fixed level of V_{Tset} , we observed increased P_{peak} displayed by the ventilator but stable P_{peak} detected by the test lung (Figure 4). Statistical analyses showed that P_{peak} displayed by the ventilator was higher than that detected by the test lung for the same V_{Tset} group and ambient pressure (Table 4). In ventilator groups with fixed V_{Tset} , P_{peak} increased obviously at raised ambient pressure with multiple comparisons, but the difference was not statistically significant in the test lung groups. At high ambient pressure (1.5-2.0 ATA), uptrends of P_{peak} were 7-13 % for the V_{Tset} 400 ml group, 9-19 % for the V_{Tset} 500 ml group, 9-20 % for the V_{Tset} 600 ml group, 6-12 % for the V_{Tset} 800 ml group and 8-18 % for the V_{Tset} 1000 ml group compared with P_{peak} displayed by the ventilator at normal ambient pressure (1.0 ATA).

Discussion

Advanced investigation showed that ordinary ventilators used at normal atmospheric pressure cannot maintain stable V_T during VCV when operated at high atmospheric pressure. Inspiratory flow provided by

the ventilator will decrease with increasing ambient pressure [7,8,9,10]. The reason is that during HBO therapy, the ambient pressure is raised by compression air, which results in a high breath gas density and has no influence on breath gas viscosity. High breath gas density results in more turbulent flow in peripheral airways according to an increased Reynold's value (>1000 , Figure 5). To obtain the same inspiratory flow, turbulent flow produces higher airway resistance than laminar flow. Hence, more driving pressure (ΔP) must be provided by the ventilator to overcome the higher airway resistance; otherwise, it will lead to decreased inspiratory flow. Unless this phenomenon is technically compensated for, hypoventilation may occur due to decreased V_T and MV [11,17]. To maintain adequate VT and MV, we need to increase the inspiratory flow as the chamber pressure increases through manual regulation or automatic compensation [7,8,9,10,16].

Evaluating V_T during VCV at high ambient pressure

During VCV, the modified Shangrila590 ventilator can provide more ΔP to overcome the greater resistance and achieve constant V_T and MV, even though V_T and MV decreased within a narrow range. In the high V_{Tset} group (800-1000 ml), the decline in V_T as the ambient pressure increased was greater than that in the low V_{Tset} group (400-600 ml) (Table 2, Figure 2). However, the degree of decline was smaller than that in previous research at the same ambient pressure scale, which resulted in a 20-56 % decline in V_T [7,9]. Nonetheless, compared with the hyperbaric ventilator Siaretron IPER 1000, a 6.5-20 % increase in V_T during VCV under 1.0 ATA to 2.2 ATA ambient pressure occurred, which is CE-certified for hyperbaric use in Europe [10]. A modified Penlon Nuffield 200 has been used in a monoplace hyperbaric chamber, fixed outside the chamber, with a 30 % decrease in V_T with ambient pressure from 1.0 ATA to 2.0 ATA [16].

When we focused on the accuracy of V_T displayed by the ventilator, it was not exactly equal to V_T detected by the test lung. For V_{Tset} between 400-600 ml, the V_T displayed by the ventilator may overestimate the actual V_T . Otherwise, for V_{Tset} between 800-1000 ml, the V_T displayed by the ventilator may underestimate the actual V_T . The difference in V_T displayed by the ventilator and by the test lung was narrow during V_{Tset} between 400-600 ml, but it was wide during V_{Tset} between 800-1000 ml. However, the accuracy of the test lung in previous studies was controversial at high ambient pressure [7,9]. We used a water tank-simulated lung in pre-experiments, which can roughly reflect the true value of ventilator V_T . The data between the ventilator and the water tank-simulated lung seemed good, but the numerical precision of the water tank-simulated lung was low. For statistical analysis, we decided to choose the Michigan test lung (5601i) for the test equipment, according to previous research [7].

During VCV, the goal of maintaining constant V_T is to take in enough O_2 and ensure expiration of CO_2 . Factors affecting the expiration of CO_2 include not only V_t but also dead space and high PaO_2 . During HBO therapy, PaO_2 is much higher than that under normobaric conditions. Under hyperbaric conditions, respiratory resistance leads to decreased breath gas flow and enlarged dead space. These may reduce exhalation of CO_2 [18,19]. In addition to the stable operation of ventilators, it is essential to monitor the

expiratory volume, arterial partial pressure of carbon dioxide (PaCO_2), transcutaneous carbon dioxide tension ($\text{P}_{\text{TC}}\text{CO}_2$), or end-tide carbon dioxide partial pressure ($\text{P}_{\text{ET}}\text{CO}_2$) [11,20].

Changes in Peak during VCV at high ambient pressure

Our data showed that the P_{peak} displayed by the ventilator increased obviously during VCV with fixed V_{Tset} in the process of ambient pressure rise (Table 4, Figure 4). As P_{peak} can reflect inspiratory resistance, the ventilator can provide more ΔP to overcome increased airway resistance to maintain stable V_{T} . Our data shown in Figure 4 supports this mechanism. However, changes in P_{peak} detected by the test lung were gentle because of the different detected positions of the ventilator and the test lung. The breathing gas flow was buffered when detected by the test lung.

Side effect of HBO in pulmonary system and preventive measures

In general, there is no risk of pulmonary barotrauma (PBT) in patients with normal lungs during HBO therapy. Based on Boyle's Law, there is potential for PBT due to lung overinflation during decompression when disease is present, such as asthma or chronic obstructive pulmonary disease (COPD) with active bronchospasm, mucous plugging, and bullous lung disease. Additionally, pneumothorax (PTX) is a potentially life-threatening phenomenon, especially given the increased risk of tension PTX during decompression. All candidates for HBO therapy must be screened for pulmonary disease to avoid increasing the risk of PBT and PTX [21].

Continuous exposure of the lungs to elevated PaO_2 , either at normobaric or hyperbaric pressure, leads to toxic effects of O_2 . Pulmonary O_2 toxicity can be avoided if O_2 is provided at the proper dose [5,22]. When FiO_2 is continuously high in normobaric environments, the lungs are at risk of O_2 toxicity: **(a)** high FiO_2 levels promote the formation of absorption atelectasis in the absence of nitrogen; **(b)** high FiO_2 levels also induce ROS-mediated damage; and **(c)** another side effect of hyperoxemia is the rise in PaCO_2 [22]. In the hyperbaric chamber, we can obtain higher PO_2 by increasing ambient pressure with lower FiO_2 to avoid absorption atelectasis. In rats, HBO exposure caused significant oxidative stress in the first 24 h. However, these effects were resolved at the end of the tenth day of HBO treatment [23]. There are two pathways for the development of CO_2 intoxication. PCO_2 is increased in inspired breathing gas or expiration of produced CO_2 is insufficient [17]. Increased PCO_2 in inspired gas may occur when gas exchange occurs in the hyperbaric chamber. To prevent raised PCO_2 levels, hyperbaric chambers must be flushed continuously with breathing gas. Increased breathing resistance in the hyperbaric chamber may decrease the expiration of produced CO_2 . Maintaining stable pulmonary ventilation and monitoring PaCO_2 by blood gas, $\text{P}_{\text{ET}}\text{CO}_2$, and $\text{P}_{\text{TC}}\text{CO}_2$ must be established during HBO therapy [11,17,21].

Work of breathing in hyperbaric environments is also a concern. Combined with the breathing equipment itself, the work of breathing will be increased compared to breathing the same gas in a normobaric environment [6]. For patients on mechanical ventilation, the endotracheal tube diameter is critical with regard to its effect on airway pressure and work of breathing [18]. During HBO therapy, we must consider

that a high breath gas density induces high airway resistance, which cannot be avoided in hyperbaric chambers. In addition to sputum aspiration and exchange for large endotracheal intubation, we can decrease airway resistance by prolonging the inspiratory time appropriately and using a helium oxygen mixture to decrease the gas density. Additionally, we can reduce the high airway resistance and breathing work by downregulating ambient pressure or upregulating the support pressure of the ventilator.

Conclusions

In summary, during HBO therapy with raised ambient pressure from 1.0 ATA to 2.0 ATA, a modified Shangrila590 ventilator made in China can provide stable V_T and MV during VCV with V_{Tset} from 400 ml to 1000 ml. During VCV, Ppeak increased obviously because of the raised ambient pressure. We will evaluate other ventilator models, such as PCV, in the future. Advanced detection of this ventilator operating in an environment of more than 2.0 ATA will be carried out in our further study.

Abbreviations

ATA: atmospheres absolute; VCV: volume-controlled ventilation; VTset: preset tide volume; VT: tide volume; Ppeak: inspiratory airway peak pressure; MV: minute volume; HBO: hyperbaric oxygen; FiO₂: inspired oxygen; ICU: intensive care unit; PaO₂: arterial partial pressure of oxygen; PO₂: pressure of oxygen; PCV: pressure-controlled ventilation; O₂: oxygen; CO₂: carbon dioxide; ΔP : driving pressure; PaCO₂: arterial partial pressure of carbon dioxide; P_{TC}CO₂: transcutaneous carbon dioxide tension; P_{ET}CO₂: end-tide carbon dioxide partial pressure; PBT: pulmonary barotrauma; COPD: chronic obstructive pulmonary disease; PTX: pneumothorax.

Declarations

Ethics approval and consent to participate

Not applicable. This study didn't involve human participants, human material, or human data. This study has been granted an exemption from our national ethics approval (Beijing Tiantan Hospital Medical Ethic Committee).

Consent for publication

Not applicable.

Availability of data and materials

All data used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that have no competing interests.

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None.

Authors' contributions

LX designed the study. CW, QY and YL completed the literature review. LX and CW redacted the protocol. LC performed the measurements and the records. JL and LC modified the ventilator. CW undertook the data statical analysis, and wrote the manuscript. ZR and YL operated and maintained the hyperbaric chambers. All authors read and approved the final manuscript.

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Tables

Due to technical limitations, table 1 to 4 is only available as a download in the Supplemental Files section.

Figures

Figure 1

The experimental configuration

Figure 2

Changes in tide volume during volume-controlled ventilation at different ambient pressure

Figure 3

Changes in minute volume during volume-controlled ventilation at different ambient pressure

Figure 4

Changes in inspiratory airway peak pressure during volume-controlled ventilation at different ambient pressure

$$Re = \dot{V} r \frac{\rho}{\eta}$$

Where: Re = Reynold's number

$\dot{V}$ = flow rate

r = airway radius

ρ = breathing gas density

η = breathing gas viscosity

L = length of airway

$Re < 1000$ Laminar flow

Re 1000-1500 Laminar & Turbulent flow

$Re > 1500$ Turbulent flow

Laminar flow

In small terminal airways

Turbulent flow

In the upper airways

$$\dot{V} = \Delta P \frac{\pi r^4}{8 L \eta}$$

$$\Delta P = k \times \dot{V}^2$$

for: k being proportional to $\frac{\rho}{r^5}$

$$\dot{V} \propto \frac{\Delta P}{\eta}$$

$$\dot{V} \propto \frac{\sqrt{\Delta P}}{\rho}$$

(W. Wetslau. Physiologic Effects of Increased Barometric Pressure. In Handbook on hyperbaric medicine.

Daniel Mathieu (Ed.). Springer-Verlag, Dordrecht, The Netherlands, 2006:41-43.)

Figure 5

Type of breathing gas flow

Supplementary Files

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