SHORT COMMUNICATION

Performance of the Uni-Vent Eagle™ Model 754 ventilator under hyperbaric conditions

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ABSTRACT

Critically ill patients needing mechanical ventilation may require hyperbaric oxygen therapy. Some institutions still use ventilators that were available prior to the advent of hyperbaric-specific units, such as the Uni-Vent Eagle™ model 754. Here we examine the performance of the Uni-Vent model 754 under hyperbaric conditions and investigate concerns of an oxygen leak in the ventilator housing, which poses a fire risk.

We studied the ventilator at 1.0, 2.4 and 2.8 ATA in assist control mode using a Michigan test lung and a variety of tidal volumes and respiratory rates. We recorded the delivered volumes, peak pressures, and oxygen percentages within the hyperbaric chamber at 2.4 and 2.8 ATA and within the ventilator housing. At those pressures the ventilator delivered approximately 25% less volume than at 1.0 ATA. We observed breath stacking at high respiratory rates, but this was blunted at both 2.4 and 2.8 ATA. Oxygen levels did not rise in the housing during our investigation. In addition, we fit a linear regression to the data comparing set tidal volumes and delivered tidal volumes in order to model the changes observed.

Hyperbaric conditions caused decreased delivered tidal volumes in a depth-dependent fashion, and oxygen levels within the housing did not rise. The Uni-Vent Eagle model 754 performed safely and effectively at depth but requires spirometry to correctly program desired ventilator settings.

INTRODUCTION

Mechanically ventilated patients occasionally require hyperbaric oxygen (HBO_2) therapy. An ideal multiplace hyperbaric chamber ventilator would be versatile enough to treat adult and pediatric patients, portable enough to fit in the restricted space of a small chamber, sturdy enough to handle hyperbaric pressures as well as transport, and have an external power source via a chamber pass-through. Although ventilators designed for HBO_2 therapy are now commercially available (e.g., VersalVent Model V1 made by Pan-America Hyperbarics, Inc.), some institutions use ventilators that were available prior to the advent of these hyperbaric-specific units [1].

Continued use of these devices may be due to cost considerations, continuity with familiar equipment with established safety records, and interchangeability with equipment outside the hyperbaric treatment area. Our institution uses one such ventilator, the Uni-Vent Eagle™ model 754, which has been shown to be an adequate replacement in HBO_2 therapy for non-electric ventilators by the United States Navy and which we have used successfully for approximately 11 years in our multiplace hyperbaric chamber [2,3].

Our study attempts to evaluate this ventilator's performance at pressures commonly used in HBO_2 therapy. We hypothesized this ventilator would deliver a lesser tidal volume depending upon the treatment depth and respiratory rate. Furthermore, we hypothesized these changes would be predictable and could be modeled mathematically. In addition, other institutions have voiced concern of an oxygen leak in the ventilator housing (personal communication with U.S. Navy Diving Medical Officers). This poses a fire risk which would be catastrophic during a hyperbaric oxygen treatment. We hypothesized that there would be no oxygen leak during our study when we would be monitoring oxygen levels within the ventilator housing.

METHODS

We investigated a Uni-Vent Eagle model 754 (Impact Instrumentation, Inc., West Caldwell, New Jersey) at 1.0, 2.4 and 2.8 atmospheres absolute (ATA) in assist-control mode using a Michigan test lung (Training Test Lung; Michigan Instruments, Grand Rapids, Michigan) and

KEYWORDS: critical care; mechanical ventilation; ventilator

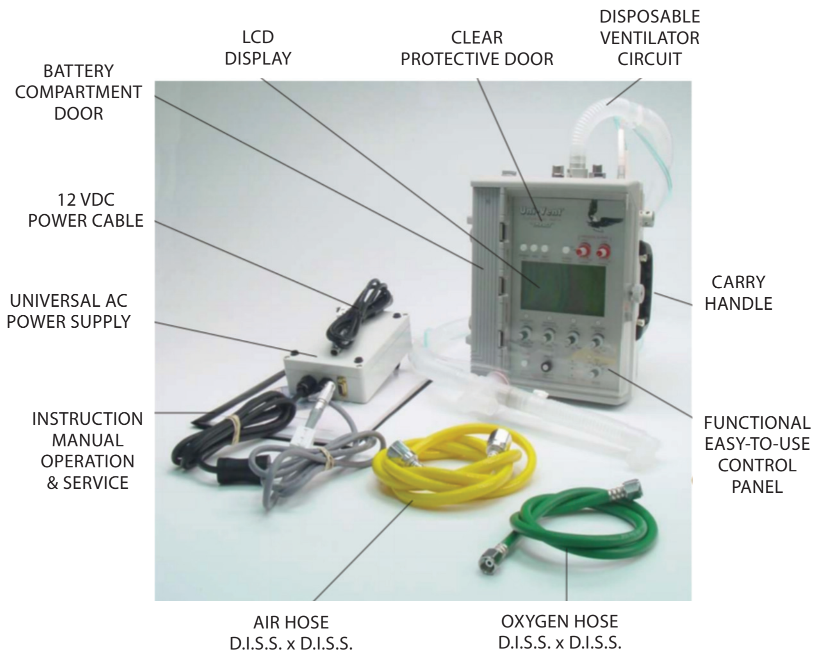
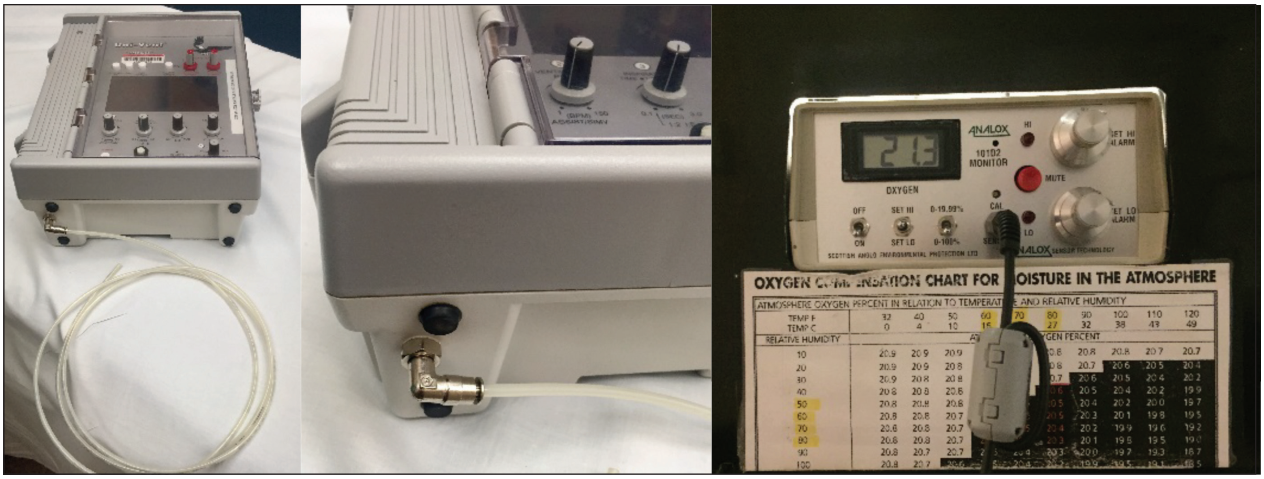


Figure 1. The Uni-Vent™ Eagle model 754 ventilator
(from the Operations Manual by Impact Instrumentation, Inc.) [4]

100% oxygen in a multiplace chamber. The Uni-Vent Eagle model 754 is a portable electronically controlled ventilator with the ability to use assist-control ventilation (ACV), synchronized intermittent mandatory ventilation (SIMV), or continuous positive airway pressure (CPAP) with or without positive end expiratory pressure (PEEP) support [4] (Figure 1). Our Uni-Vent™ Eagle model 754 ventilator was manufactured in 2009 and undergoes preventive maintenance yearly. We use a multiplace/multilock class A hyperbaric chamber, 6 feet in diameter and 23 feet long, rated to 6.0 ATA with a 75psi maximum working pressure. Pacific Coast Welding and Machine, Inc. manufactured the chamber in 1986. The Michigan test lung is a two-chamber portable dynamic lung simulator that allows analog breath-by-breath volume measurement and has been used extensively in other studies involving ventilator performance [5-8]. We fixed the test lung compliance throughout our trials to 0.05 L/cmH2O, consistent with a normal adult mechanically ventilated lung according to the test lung manual and published data [3,9,10].

We set the ventilator with tidal volumes ranging from 100-700mL, in 100mL increments for one-minute intervals. At the end of each of these one-minute intervals we recorded delivered volumes, peak pressures, and the oxygen percentage within the chamber and within the ventilator housing. At each depth we used three different respiratory rates (12, 20 and 30 breaths/minute), representing the range that we typically use in treatments. We held the inspiratory time to expiratory time (I:E) ratio at 12 and 20 breaths/minute to 1:2, while at 30 breaths/minute we held it to 1:1, as the ventilator was unable to maintain a 1:2 ratio. To measure the oxygen within the ventilator we drilled a port into the housing and connected it to one of two sample ports inside the hyperbaric chamber that are connected to the outside oxygen analyzer (Model 101D2, Analox, Huntington Beach, California) (Figure 2). The outside attendant sampled the internal oxygen concentration within the ventilator every five minutes during the trial. In order to maintain investigator safety and stay within no-stop limits, total dive time was limited to 60 minutes.

Figure 2. Sample port



The sample port (with close-up view) drilled into the ventilator housing in order to sample the internal oxygen concentration using the Analox 101D2 monitor (bottom panel).

Using the freely available statistical package R (*http://www.rstudio.com*), we fit a linear regression to the data at 2.4 and 2.8 ATA comparing set tidal volumes and delivered tidal volumes [11]. We fit a linear regression model for each respiratory rate separately (for 12 breaths/minute and 20 breaths/minute) but did not use the 30 breaths/minute data due to confounding issues (see the Results section).

RESULTS

At 1.0 ATA, the set volume equaled the delivered volume for respiratory rates of 12 and 20 breaths/minute. At a rate of 30 breaths/minute, however, breath stacking occurred above set volumes of 300mL, which manifested as incomplete emptying of the Michigan test lung and elevated the delivered tidal volume (Figure 3). Under hyperbaric conditions at 2.4 and 2.8 ATA, the ventilator delivered less volume than at 1.0 ATA or the set volume in a depth-dependent fashion (Figures 4-5, respectively).

The respiratory rate of 30 breaths/minute proved a special case across all pressures as we observed breath stacking – especially with set tidal volumes above 300mL. Using the respiratory rate of 30 breaths/minute at both 2.4 and 2.8 ATA, the decrease in delivered tidal volume under hyperbaric conditions attenuated the breath stacking effect on the Michigan test lung volume readings (Figures 4-5, respectively). At lower set tidal volumes the delivered volume readings were higher than those with the same volume at lower respiratory rates. For example at 2.8 ATA, the ventilator delivered 300mL when set to 400mL for both 12 breaths/minute and 20 breaths/minute but delivered 375mL at 30 breaths/minute (Figure 5). The delivered volume of 375mL was still less than the delivered volume of 425mL under the same ventilator settings at 1.0 ATA (Figure 3). On the other hand, the higher set volumes continued to show breath stacking that increased the delivered tidal volume in comparison to the set volume under the hyperbaric conditions but to a lesser degree than at 1.0 ATA. For example when set for 700mL, the ventilator delivered 725mL at 30 breaths/minute at 2.8 ATA in comparison to only 500mL delivered at 20 breaths/minute at the same 2.8 ATA (Figure 5). The delivered 725mL, however, was less than the 800mL delivered at 30 breaths/minute at 1.0 ATA, demonstrating the hyperbaric pressure effect on the observed breath stacking (Figure 3).

Peak pressures generally remained stable or decreased with increased hyperbaric conditions in a depth-dependent fashion (Figure 6). For example using a set tidal volume of 600mL at 12 breaths/minute, the peak pressure at 1.0 ATA was 15 ccmH2O while at 2.4 ATA it was

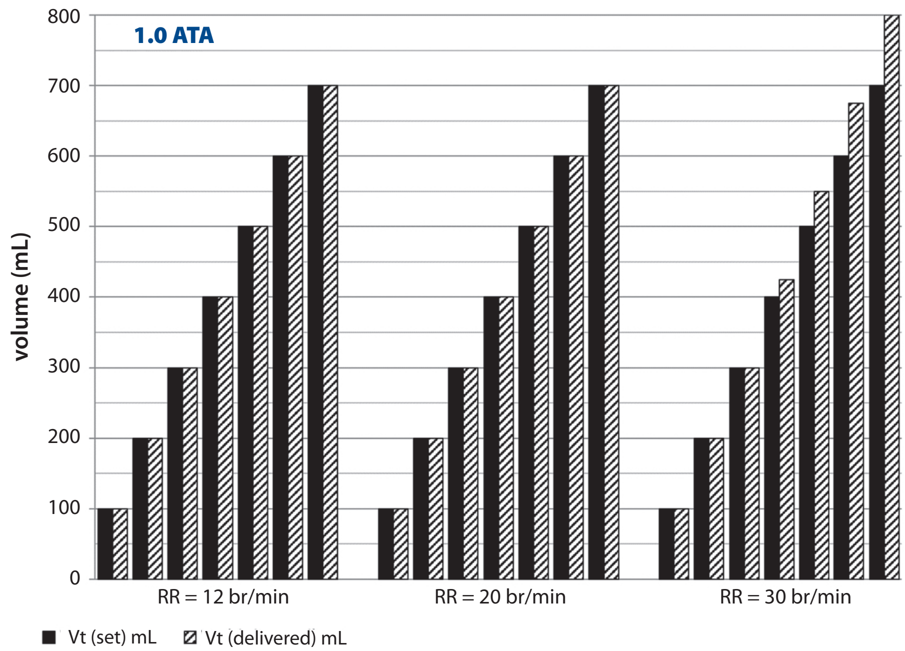


Figure 3

A comparison between tidal volumes set and delivered by the ventilator at 1.0 ATA.

Breath stacking occurred at the tidal volumes higher than 300mL at the rate of 30 br/min.

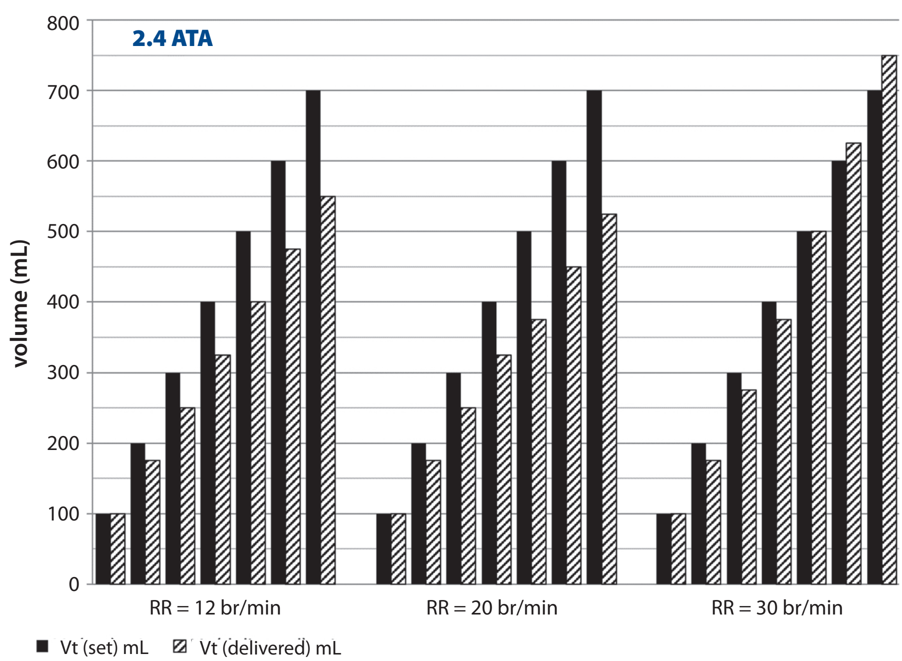


Figure 4

A comparison between tidal volumes set and delivered by the ventilator at 2.4 ATA.

Hyperbaric conditions reduced the delivered volumes from the ventilator by a variable amount. Breath stacking occurred at the tidal volumes higher than 200mL at the rate of 30 br/min, blunting the hyperbaric effect of decreased delivered volumes.

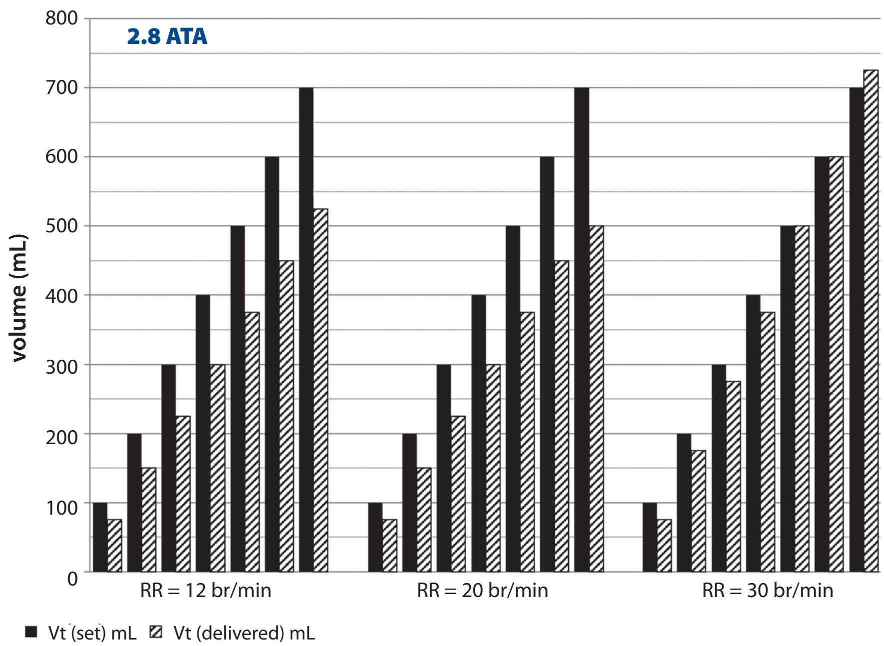


Figure 5

A comparison between tidal volumes set and delivered by the ventilator at 2.8 ATA.

Hyperbaric conditions reduced the delivered volumes from the ventilator by a variable amount but to a greater effect than at 2.4ATA. Breath stacking occurred at the tidal volumes higher than 100mL at the rate of 30 br/min, blunting the hyperbaric effect of decreased delivered volumes.

14 ccmH2O and at 2.8 ATA it was 13 cmH2O (Figure 6, top panel). The peak pressures increased with higher respiratory rates and when breath stacking occurred. To illustrate, using a set tidal volume of 700mL at 30 breaths/minute, the peak pressure at 1.0 ATA was 21 cmH2O, while at 2.4 ATA it was 22 cmH2O and at 2.8 ATA it was 23 cmH2O (Figure 6, bottom panel).

Oxygen levels did not rise in the housing during our investigation and stayed well below the National Fire Protection Administration mandated maximum level of 23.5% oxygen. At 1.0 ATA, the ambient oxygen concentration was 21% as was the ventilator's housing. Under hyperbaric conditions, the ambient oxygen and the ventilator housing remained tightly correlated and did not deviate from the range of 20.1-20.4% (Table 1).

The linear regression modeling revealed that using the respiratory rate of 12 breaths/minute at 2.4 ATA, the relationship between set and delivered volumes (mL) was as follows:

delivered volume = 0.75(set volume) + 25*

Meanwhile using the respiratory rate of 12 breaths/minute at 2.8ATA, the relationship between set and delivered volumes (mL) was as follows:

delivered volume = 0.75(set volume).*

For both 2.4 and 2.8 ATA at 12 breaths/minute, the regression model perfectly fits the data (i.e., all residuals are zero). Linear regression models assume residuals have a mean of zero and a constant variance [12]. In the case of 2.4 ATA at 20 breaths/minute the residuals are large at intermediate values of set tidal volume (i.e., the mean is not zero and variance is not constant). In the case of 2.8 ATA at 20 breaths/minute the residuals increase with increasing set tidal volume (i.e., the variance is not constant). Meanwhile for the 30 breaths/minute condition we did not attempt these analyses due to the observed breath stacking.

DISCUSSION

Data from this study support our hypothesis that the Uni-Vent Eagle model 754 delivers tidal volumes lower than set volumes under hyperbaric conditions in a depth-dependent fashion. Anecdotally, our staff have been aware of the decreased delivered tidal volumes compared to the set tidal volumes with this ventilator and manually correct the settings at depth during treatments with the help of a spirometer (Adult Spirometer Model

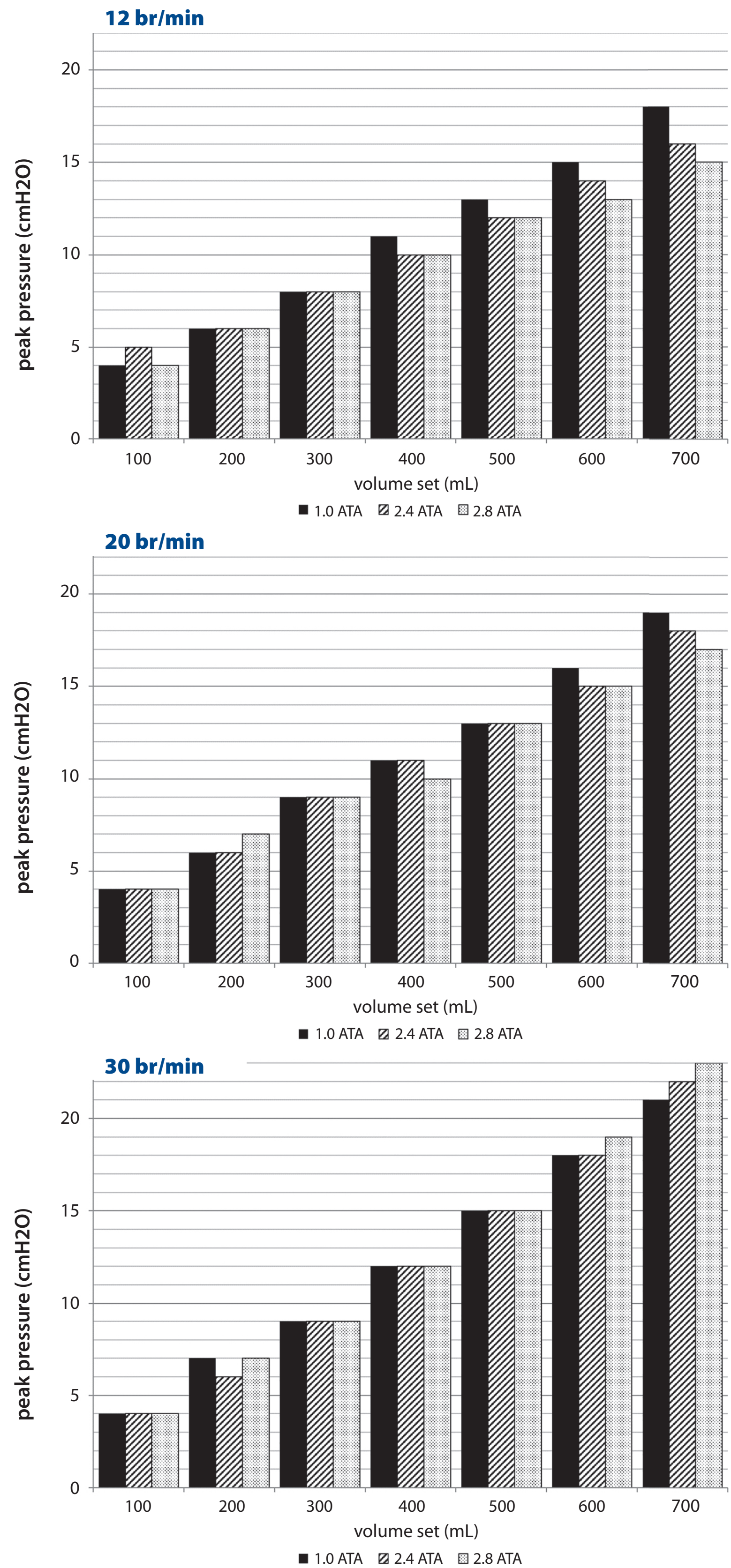


Figure 6. Peak pressures increased with faster respiratory rates and breath stacking in the higher set tidal volumes, especially at the 30br/min setting.

Table 1. Oxygen concentration ranges

	O_2 chamber (%)	O_2 ventilator (%)
1.0 ATA	21	21
2.4 ATA	20.1	20.1 – 20.3
2.8 ATA	20.1 – 20.4	20.1 – 20.3

Oxygen concentration ranges measured inside the hyperbaric chamber and inside the ventilator housing. No oxygen leak was detected as demonstrated by the close agreement between measured chamber oxygen and ventilator housing oxygen levels.

8800, Boehringer Laboratories, Phoenixville, Pennsylvania). Similar results have been reported elsewhere and attributed to the increased density of compressed gas, leading to decreased volume flow for a constant degree of opening of the inspiratory valve of the ventilator [1].

Peak pressures, meanwhile, increased with respiratory rate but decreased under hyperbaric conditions, likely related to reduced flow. When breath stacking occurred, however, the pressures increased relative to the baseline pressures observed at 1.0 ATA – which is expected given the incomplete emptying that creates breath stacking. Lung protective ventilation has been a mainstay of management of mechanically ventilated patients since the Acute Respiratory Distress Syndrome Network study in 2000 demonstrated significant reductions in patient mortality and an increased number of days without ventilator use [13]. One of the key features of that lung protective strategy is maintaining ventilator plateau pressure at no more than 30 cmH2O. The peak inspiratory pressure is typically higher than the plateau pressure, and none of our observed peak inspiratory pressures exceeded the 30 cmH2O recommendation. Were breath stacking allowed to persist beyond the time interval studied, we would expect the peak pressure to rise to dangerously high levels. Hence, we advise caution with the ventilator when programming higher respiratory rates due to the propensity to breath stack. Based on our clinical experience treating ventilated patients with this ventilator, we have not observed breath stacking nor been limited by its performance. The difference between our clinical experience and the results of this study may be explained by the limitations of the artificial test lung, which uses a spring to approximate the human thorax. In obstructive lung diseases with higher lung compliances such as asthma, we anticipate the breath stacking would occur at even slower respiratory rates. The practice of medically optimizing patients prior to initiating HBO_2 therapy may also contribute to the lack of observed breath stacking among our patients.

While we successfully mathematically modeled the relationship between set and delivered tidal volumes for a respiratory rate of 12 breaths/minute, we were unable to do so at other respiratory rates. The relationship we successfully modeled represents an initial guide to controlling the ventilator and requires further validation, as other factors such as alternate respiratory rates and lung compliance values will affect this relationship. Further studies should be done to verify this relationship, as this study was limited by one data point per pressure, respiratory rate, and set tidal volume. Nonetheless, the relationship can be used clinically by staff as a starting point for volume titration of the ventilation, confirming with spirometry.

Despite a theoretical concern of fire risk through an oxygen leak within the ventilator housing where the electronics are located, we detected no such leak in our study and confirmed our initial hypothesis. While an intermittent leak or a failure in the future remains a possibility, institutional experience with this ventilator reassures us that with regular care and maintenance the risk of such a leak is extremely low. If the concern persists, drilling a port through which the oxygen level could be sampled from within the housing represents a potential risk mitigation strategy. Such modifications may have implications in manufacturer support and warranty coverage however, so we advise caution before undertaking such modifications.

Limitations

We performed this study using only a single multilevel dive and one single ventilator. The ventilator was used in ACV mode only, and its performance could vary differently in another mode such as SIMV. ACV mode, however, is overwhelmingly the mode used in our patients. In addition, we investigated the ventilator's performance using only one value for compliance. Compliance values consistent with obstructive or restrictive lung diseases may lead to different results in delivered volumes, peak pressures, and breath stacking.

CONCLUSION

The Uni-Vent Eagle model 754 meets many of the ideal hyperbaric ventilator criteria such as versatility and portability and has been used at our facility successfully since 2010. It performs safely and effectively at depth but requires spirometric analysis to correctly program the desired ventilator volumes since it delivers lower tidal volumes under hyperbaric conditions. We observed breath stacking at higher respiratory rates and volumes but feel that it is a manageable risk. In addition to spirometry, constant monitoring of vital signs and the patient's clinical exam remain mainstays in our management of ventilated patients.

Conflict of interest statement

The authors have declared no conflicts of interest.

REFERENCES

1. Kot J. Medical equipment for multiplace hyperbaric chambers part II: Ventilators. Eur J Underw Hyperb Med. 2006;7(1):1605-9204.

2. Stanga DF, Beck G, Chimiak J. Evaluation of respiratory support devices for use in the hyperbaric chamber. Nav Exp Diving Unit. 2003;TR 03-18.

3. Hennessey PJ. Evaluation of the Uni-Vent TM Eagle™ Model 754 ventilator for use in the surface recompression chambers (SRC) of the Submarine Rescue Diving And Recompression System (SRDRS). Nav Exp Diving Unit. 2007;TR 07-03.

4. Impact Instrumentation Inc. Operation Manual Portable, Self-Contained Ventilation System Uni-Vent® EagleTM 700 Series Model 754. 1997.

5. Thille AW, Lyazidi A, Richard JCM, Galia F, Brochard L. A bench study of intensive-care-unit ventilators: New versus old and turbine-based versus compressed gas-based ventilators. Intensive Care Med. 2009;35(8):1368-1376. PMID: 19352622

6. Lefebvre JC, Lyazidi A, Parceiro M, Sferrazza Papa GF, et al. Bench testing of a new hyperbaric chamber ventilator at different atmospheric pressures. Intensive Care Med. 2012;38(8):1400-1404. PMID: 22588650

7. Beloncle F, Piquilloud L, Olivier PY, Vuillermoz A, et al. Accuracy of P0.1 measurements performed by ICU ventilators: a bench study. Ann Intensive Care. Springer Verlag; 2019 Dec 1;9(1).

8. Chen GQ, Sun XM, Wang YM, Zhou YM, et al. Additional expiratory resistance elevates airway pressure and lung volume during high-flow tracheal oxygen via tracheostomy. Sci Rep. Nature Publishing Group; 2019 Dec 1;9(1). PMID: 31601935

9. Michigan Instruments. Training and Test Lung Operation Manual [Internet]. 2020. Available from: www.michiganinstruments.com

10. Arnal J-M, Garnero A, Saoli M, Chatburn RL, Rrt-Nps Faarc M. Parameters for simulation of adult subjects during mechanical ventilation. 2018 [cited 2020 Dec 21]; Available from: www.iso.org/standard/51141.html,

11. R Core Team. R: A language and environment for statistical computing [Internet]. R Foundation for Statistical Computing. 2020. Available from: https://www.r-project.org/

12. Hogg R, Craig A. Introduction to mathematical statistics. 3rd ed. New York, NY: The MacMillan Company; 1970.

13. Brower R, Matthay M, Morris A, Schoenfeld D, et al. Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. N Engl J Med [Internet]. (NEJM/MMS); 2000 May 4 [cited 2021 Feb 24];342(18):1301–1308. Available from: https://pubmed.ncbi.nlm.nih.gov/10793162/ PMID: 10793162