Performance of the Oxylog® 1000 portable ventilator in a hyperbaric environment

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Key words
Equipment; Performance; Pressure; Hyperbaric research; Safety

Abstract
(Lie SA, Loy ST, Lee CC, Kim SJ, Soh CR. Performance of the Oxylog® 1000 portable ventilator in a hyperbaric environment. Diving and Hyperbaric Medicine. 2018 June;48(2):102–106. doi. 10.28920/dhm48.2.102-106. PMID: 29888382.)
Introduction: The management of mechanically ventilated patients in the hyperbaric environment requires knowledge of how the physical properties of gases change under pressure and how this affects the operation of the ventilator. The primary objective of this study was to test the performance of the Dräger Oxylog 1000® ventilator in a hyperbaric environment.
Methods: Each of two ventilators was connected to a mechanical test lung system with an in-built pressure gauge. We used a Wright's respirometer to measure the tidal volumes. The same ventilator settings were tested under varying environmental pressures from ambient (101.3 kPa) to 18 meters' sea water (284 kPa) in a multiplace hyperbaric chamber.
Results: A decrease was found in tidal volume, decrease in airway pressure and increase in respiratory rate delivered by the Dräger Oxylog 1000 portable ventilator with increasing pressures to 284 kPa.
Discussion: These findings can be explained by the operating principles of the Oxylog 1000, which is a time-controlled, constant-volume ventilator that functions as a flow chopper. Even between the two Oxylog 1000 ventilators tested there were different absolute changes in tidal volume, airway pressures and respiratory rates at various depths. Hence, the trend of changes in these variables is probably more important than absolute values.
Conclusion: In summary, understanding the trend of changes in ventilator variables will allow clinicians to make appropriate corrections in ventilator settings and carefully monitor adequacy of ventilation to prevent adverse ventilator-associated events. The Dräger Oxylog 1000 portable ventilator is an adequate back-up ventilator for use with straight-forward, ventilator-dependent patients undergoing hyperbaric treatment.

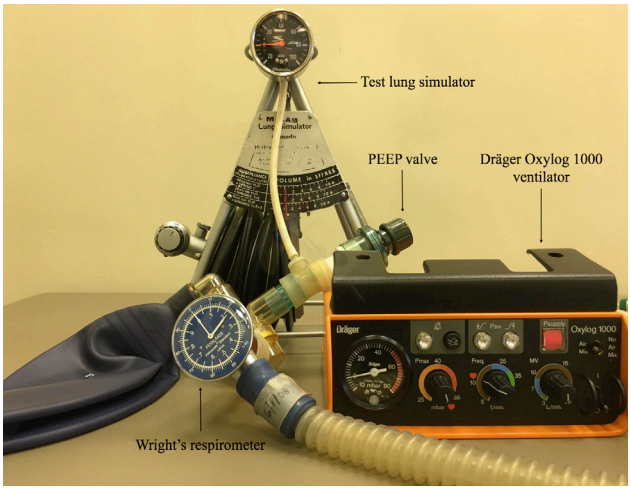
Introduction

Treatment of mechanically ventilated, critically ill patients in the hyperbaric chamber presents unique challenges to the clinician. It requires knowledge of how the physical properties of gases change under pressure, and how this affects the operation of the ventilator before appropriate technical modification or change of settings can be undertaken.[1] Engineering challenges include lack of access to standard high voltage alternating current power supply and risks of fire in a high-pressure, high-oxygen (O_2) environment from sparks generated by motor parts and combustibility of standard lubricants. Hence, electrical equipment for use in the hyperbaric chamber should be *"CE marked"* and validated safe for use.[2] Of equal safety concern for patients is ensuring consistent performance of monitoring devices, infusion pumps and mechanical ventilators under changing ambient pressures.

The performance of all pneumatic devices in a hyperbaric environment is altered by the increase in ambient pressure and gas density. The flow resistance of airways also increases under hyperbaric conditions.[3] As a result, flow of gas in and out of the lungs is slowed, reducing the flow delivered by the ventilator.[4] Such performance characteristics of ventilators under hyperbaric conditions are hard to predict as they differ widely depending on underlying operating mechanics. Most studies done on various ventilator models demonstrate a lower tidal volume delivered compared to the actual set volume, which may lead to hypoventilation if unrecognized.[5–8] As a result, only a few ventilators have been "*CE marked*" for hyperbaric use. Many other simpler transport ventilators are generally capable of functioning in such non-standard conditions, but with recognition of their limitations and modification of settings.[1,9]

The hyperbaric chamber in our institution has a pneumatic powered Dräger Oxylog® 1000 portable patient ventilator and a Siemens Servo 900C ventilator, which is CE-approved. The Dräger Oxylog 1000 is a time controlled, constant volume ventilator that functions as a flow chopper for which there is a paucity of data describing its performance under hyperbaric conditions.[1] Extrapolating from studies that demonstrate a fall in respiratory rate and rise in tidal

Figure 1
Experimental setup in the hyperbaric chamber; the Oxylog 1000® ventilator is connected to a mechanical test lung system with an in-built pressure gauge; positive end expiratory pressure is provided by an Ambu© PEEP valve; a Wright's respirometer measured delivered tidal volumes



volume and minute volume in a hypobaric environment with the Dräger Oxylog,[10,11] it was hypothesized that the converse would happen in a hyperbaric environment – an increase in respiratory rate and fall in tidal volume. Hence, the primary objective of this study was to test the performance of the Oxylog 1000 ventilator in a hyperbaric environment. Clinicians looking after critically ill patients in the hyperbaric environment need to be cognizant of such differences and tailor their monitoring and ventilator strategies accordingly.

Materials and methods

This study was conducted in a multiplace hyperbaric chamber in a tertiary referral centre. Two Oxylog 1000 ventilators were tested. We connected each ventilator to a mechanical test lung system with an in-built pressure gauge (Ohmeda©) that can simulate low lung compliance (dynamic compliance of 20 ml·cmH_2O^{-1}) and high airway resistance, mimicking what would likely be observed in a patient with acute respiratory distress syndrome, with an obstructive airway pattern. Delivered tidal volume (TV) was measured with a Wright's spirometer and airway pressure (P_{aw}) with the in-built pressure gauge of the test lung, rather than the displayed inspiratory airway pressure on the ventilator, for more accurate representation of airway pressure in the test lung. Positive end expiratory pressure (PEEP) was provided using an external PEEP valve (Ambu©). The respiratory rate on the ventilator was set at 15 breaths per minute (min) and actual respiratory rate (RR) was checked manually by counting respiratory movements of the test lung for 1 min. We performed the measurements at two different PEEP levels (0 and 5 cmH_2O) and two different settings for fractional inspired concentration of oxygen (FiO_2) by switching between the "*Air Mix*" mode and "*No Air Mix*" mode on the ventilator. "*Air Mix*" corresponds to a FiO_2 of 60% O_2 by volume (± 10% for minute ventilation (MV) greater than 7 L·min^{-1}) whereas the "*No Air Mix*" mode corresponds to a FiO_2 of 100% by volume under standard manufacturer conditions. MV was set at 20 L·min^{-1} and the upper alarm limit for airway pressure (P_{max}) at 55 cmH_2O. RR, TV and P_{aw} were measured under various pressures ranging from ambient pressure (101.3 kilopascal, kPa) to 284 kPa (equivalent to a depth of 18.4 metres' sea water). Both ventilators were tested under identical conditions, as shown in Figure 1. Internal review board approval was not required as this is an equipment performance experimental study with no research subjects.

Results

The measured RR, TV and P_{aw} obtained at various depths for the two ventilators are detailed in Tables 1 and 2 ("*Air Mix*", FiO_2 of 60%) and Tables 3 and 4 ("*No Air Mix*", FiO_2 of 100%). With increasing pressure from ambient to 284 kPa, tidal volumes delivered in both O_2 modes decreased by up to 64%. This decrease in delivered tidal volume was less at a PEEP of 5 cmH_2O compared to PEEP of 0 cmH_2O. P_{aw} decreased consistently by up to 50% compared to that at 101.3 kPa, whilst the increase in RR with increasing pressure was substantial (up to 180%). Trends in the changes in TV, RR and P_{aw} appeared to be independent of FiO_2 and PEEP levels. The change in MV was inconsistent, with a trend towards achieving a greater than set MV on the ventilator with increasing depth. This is contributed to by the greatly increased RR. Whilst the trends of decreased TV and P_{aw} and increased RR were similar in the two ventilators tested under identical conditions, the actual values observed differed between the two.

Discussion

Our findings of a decreased TV and P_{aw} and increased RR delivered by the Dräger Oxylog 1000 portable ventilator with increasing pressure up to 284 kPa are consistent with the hypothesis posed. The opposite trends were reported in a study of the Oxylog 1000 ventilator under hypobaric conditions from 17 to 3,048 metres altitude.[10] These findings can be explained by the operating principles of the ventilator. The Oxylog 1000 is a time-controlled, constant-volume ventilator that functions as a flow chopper.[12] It has no electronic parts, allowing its safe use in a hyperbaric chamber. Cycling is triggered by a change in pressure in the capacitance chamber caused by a fixed mass of gas. This mass of gas entering the capacitance chamber is controlled by a rotating needle valve linked to respiratory rate. Although mass flow across the valve is increased under hyperbaric conditions, the smaller expansion due to Boyle's law combined with the effect of the shorter inspiratory time means that a smaller TV is delivered at the same ventilator setting at pressure.[10]

Table 1

Oxylog® 1000 ventilator 1, "*Air Mix*" (FiO_2 of ~60%), effect of change in pressure on TV, Paw and RR at PEEP 0 and 5 cmH_2O; ventilator settings – MV 15 $L{\cdot}min^{-1}$, RR 15 per min, "*Air Mix*"; PEEP – positive end expiratory pressure; TV – tidal volume; Paw – airway pressure; RR – respiratory rate; MV – achieved minute ventilation based on TV x RR; * – percentage change in measurement from 101.3 to 284 kPa

Pressure	**PEEP 0** (cm H_2O)				**PEEP 5** (cm H_2O)			
(kPa)	TV (ml)	Paw (cmH_2O)	RR (min^{-1})	MV ($L{\cdot}min^{-1}$)	TV (ml)	Paw (cmH_2O)	RR (min^{-1})	MV ($L{\cdot}min^{-1}$)
101.3	900	50	15	13.5	650	45	15	9.75
162	800	45	22	17.6	650	45	26	16.9
223	550	35	30	16.5	550	40	30	16.5
284	400	30	38	15.2	400	35	39	15.6
% change*	-56	-40	+153		-39	-22	160	

Table 2

Oxylog® 1000 ventilator 2, "*Air Mix*" (FiO2 of ~60%), effect of change in pressure on TV, Paw and RR at PEEP 0 and 5 cmH_2O; ventilator settings – MV 15 $L{\cdot}min^{-1}$, RR 15 per min, "*Air Mix*"; PEEP – positive end expiratory pressure; TV – tidal volume; Paw – airway pressure; RR – respiratory rate; MV – achieved minute ventilation based on TV x RR; * – percentage change in measurement from 101.3 to 284 kPa

Pressure	**PEEP 0** (cm H_2O)				**PEEP 5** (cm H_2O)			
(kPa)	TV (ml)	Paw (cmH_2O)	RR (min^{-1})	MV ($L{\cdot}min^{-1}$)	TV (ml)	Paw (cmH_2O)	RR (min^{-1})	MV ($L{\cdot}min^{-1}$)
101.30	800	50	15	12	750	55	15	11.3
162	750	40	23	17.3	700	55	25	17.5
223	500	30	33	16.5	550	40	33	18.2
284	400	25	42	16.8	400	30	42	16.8
% change*	-50	-50	+180		-47	-45	+180	

Table 3

Oxylog® 1000 ventilator 1, "*No Air Mix*" (FiO2 of 100%); effect of change in pressure on TV, Paw and RR at PEEP 0 and 5 cmH_2O; ventilator settings – MV 15 $L{\cdot}min^{-1}$, RR 15 per min, "*No Air Mix*"; PEEP – positive end expiratory pressure; TV – tidal volume; Paw – airway pressure; RR – respiratory rate; MV – achieved minute ventilation based on TV x RR; * – percentage change in measurement from 101.3 to 284 kPa

Pressure	**PEEP 0** (cm H_2O)				**PEEP 5** (cm H_2O)			
(kPa)	TV (ml)	P_{aw} (cmH_2O)	RR (/min)	MV ($L{\cdot}min^{-1}$)	TV (ml)	Paw (cmH_2O)	RR (min^{-1})	MV ($L{\cdot}min^{-1}$)
101.3	900	50	15	13.5	600	45	15	9
162	800	45	20	16	600	45	19	11.4
223	600	35	28	16.8	580	40	28	16.2
284	500	30	35	17.5	450	35	35	15.8
*% change	-44	-40	+133		-25	-22	+133	

Table 4

Oxylog® 1000 ventilator 2, "*No Air Mix*" (FiO2 of 100%); effect of change in pressure on TV, Paw and RR at PEEP 0 and 5 cmH2O; ventilator settings – MV 15 $L{\cdot}min^{-1}$, RR 15 per min, "*No Air Mix*"; PEEP – positive end expiratory pressure; TV – tidal volume; Paw – airway pressure; RR – respiratory rate; MV – achieved minute ventilation based on TV x RR; *% change – percentage change in measurement from 101.3 to 284 kPa

Pressure	**PEEP 0** (cm H_2O)				**PEEP 5** (cm H_2O)			
(kPa)	TV (ml)	Paw (cmH_2O)	RR (min)	MV ($L{\cdot}min^{-1}$)	TV (ml)	Paw (cmH_2O)	RR (min^{-1})	MV ($L{\cdot}min^{-1}$)
101.3	1100	50	15	16.5	800	55	15	12
162	800	45	21	16.8	750	55	21	15.8
223	500	30	30	15	550	40	30	16.5
284	400	25	38	15.2	450	30	38	17.1
% change*	-64	-50	+153		-44	-46	+153	

The effect of smaller TV leads to lower P_{aw} as depth increases. Overall, despite the decrease in TV, the actual MV achieved was greater than the programmed MV on the ventilator, although this effect was varied and inconsistent. This can be explained by the fact that TV is likely pressure-limited at shallower depths. As TV falls with increasing pressure, it is no longer pressure-limited and the MV subsequently increases. Notably, the two Oxylog 1000 ventilators (even though they were of the same model) performed differently under identical simulated test conditions, producing different absolute changes in TV, RR and P_{aw} at various depths. Therefore, one must bear in mind always that the trend of changes in these variables is probably more important than absolute values since these will be largely unpredictable.

LIMITATIONS

Firstly, we simulated a depth of up to only 284 kPa. Beyond this, there would be further changes in delivered ventilator variables or device malfunction that were not seen.

Secondly, we did not measure the actual delivered FiO_2. The Oxylog 1000 delivers 100% O_2 when there is "*No Air Mix*", or approximately 60% O_2 through a venturi injector when there is "*Air Mix*". In the "*Air Mix*" mode, the O_2 concentration may be increased in situations where there is a high P_{aw} and applied TV is reduced. This is due to the physical characteristics of the injector used for air mixing where the suction effect of injectors decrease with increasing back pressure so less air will be mixed.[12] This has implications in patients who require tight control of FiO_2 and increases the risk of O_2 toxicity.

Thirdly, we assumed that the PEEP generated by the attached AMBU PEEP valve used in the experimental setup was affected mainly by the setting on the valve and not by changes in the ambient pressure in the chamber. In our experiment, the exhaust was dumped into the chamber environment rather than an independent exhaust so the pressure on the exit side of the AMBU PEEP valve will be equal to the chamber pressure. As such, the PEEP setting on the AMBU PEEP valve should approximate the generated PEEP at surface pressure. If on the other hand, for example, under clinical conditions, the exhaust from the ventilator is connected directly to the dumping system of the chamber so as to prevent dumping oxygen into the chamber environment, the opening pressure of the exhaust valve of the dumping system may present a pressure to the exhaust of the ventilator circuit which may then result in a PEEP which differs from the setting on the AMBU PEEP valve. This may then result in difficulties in setting the PEEP accurately and merits further investigation.

Lastly, the Wright respirometer (functioning on the rotating vane principle) used in our study has been shown to overestimate volumes in a hyperbaric environment where gas has greater density than that used for calibration.[4,13] This overestimation can be as much as 18% at 284 kPa.[14] This means that tidal volumes achieved in our study may in fact be an overestimate of actual tidal volumes delivered. As such, volume calibration with a syringe is often used to accurately measure tidal volume in the hyperbaric chamber. In a comparison between the Wright respirometer and Dräger Volumeter 3000, the Volumeter showed a high degree of precision, but accuracy of the Wright respirometer varied with both gas flow and pressure.[4] In another study, good correlation at modest volumes and pressures (up to 254 kPa) between volumes measured by the Wright respirometer and a calibrated displacement lung ventilation performance tester were reported, supporting "*the use of the Wright respirometer alone for monitoring ventilation in clinical practice*".[15] We felt that trends in the changes in achieved ventilation variables would be more important than absolute values (which may differ even between two ventilators of the same model), hence, the Wright's respirometer was sufficient for our research intent.

Conclusions

The functioning of the Dräger Oxylog 1000 portable ventilator is altered under hyperbaric conditions. There is a trend towards decrease in delivered TV and Paw and an increase in RR, while maintaining (or even increasing) achieved MV. Understanding this, the Dräger Oxylog 1000 portable ventilator is an adequate back-up ventilator for use with straight-forward, ventilator-dependent patients undergoing hyperbaric treatment. Clinicians should be cognizant of the differences and appropriate corrections in ventilator settings (where possible) and constant monitoring of the adequacy of ventilation should be performed to prevent adverse ventilator-associated events.

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Acknowledgement

The authors wish to thank Dr Yan Wing Wa (Department of Intensive Care, Pamela Youde Nethersole Eastern Hospital) for his valuable and constructive suggestions during the planning and development of this project.

Funding and conflicts of interest: nil

Submitted: 15 November 2017; revised 08 February 2018
Accepted: 25 March 2018