Ventilator performance under hyperbaric conditions: a study of the Servo 900C ventilator

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Key words
Ventilators, equipment, hyperbaric oxygen, hyperbaric research

Abstract

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When critically ill individuals receive hyperbaric oxygen therapy (HBOT), adequate and reliable ventilation is of great importance. The Servo 900C ventilator is widely used in this setting but its performance at pressure has been incompletely characterised.

Aims of the study:

1. To establish if the Servo 900C ventilator exhibits a reduction in delivered minute volume (MV) when used in synchronised intermittent mandatory ventilation (SIMV) mode at the maximum pressure commonly utilised in hyperbaric medicine practice.
2. If so, to calculate the correction factor(s) that needs to be applied to the ventilator settings in order to maintain delivery of the desired MV whilst at 283 kPa.

Methods: Ventilation using the Servo 900C ventilator was simulated with a test lung at sea-level atmospheric pressure (101.3 kPa) and at a pressure of 283 kPa in a hyperbaric chamber. The ventilator was operated in synchronised intermittent mandatory ventilation (SIMV) mode. Gases were collected from the exhaust valve of the ventilator to measure minute volume during simulations.

Results: Significant differences exist between the MV delivered at 101.3 kPa and that delivered at 283 kPa, for ventilator MV settings of 1.0, 10 and 15 L.min^{-1}. It is possible to fully compensate for the reduction in delivered MV at a desired setting of 1 L.min^{-1} but full compensation cannot be achieved for set MVs of 10 and 15 L.min^{-1}.

Conclusions: When using the Servo 900C ventilator in SIMV mode in a hyperbaric chamber at 283 kPa, it is possible to achieve delivery of desired MV at the lower settings. However, it is not possible to deliver MVs of 10 L.min^{-1} or more at this pressure. This has implications for the ventilation of adult patients who concurrently require HBOT.

Introduction

Critically ill patients who receive hyperbaric oxygen therapy (HBOT) may in some circumstances need concurrent mechanical ventilation. Variations in ventilator performance due to changes in ambient pressures associated with HBOT may have the potential for life-threatening consequences if not detected and corrected.[1,2]

As technology has progressed, ventilators with more complex ventilation strategies are being used within hyperbaric chambers. The ventilators used are typically designed to operate at atmospheric pressures between sea level and moderate altitude only. When such ventilators are used in a hyperbaric chamber at raised atmospheric pressure there may be differences between *set* ventilation parameters and what is *actually* delivered to the patient.[3]

The aim of this study was to establish if, at raised atmospheric pressure, a Seimens Servo 900C® (Seimens, Elena AB, Solna, Sweden) ventilator exhibited significant reductions in delivered versus set minute volume (MV). Further it aimed to establish the correction necessary to maintain the desired volumetrically constant MV at a chamber pressure of 283 kPa across a range of minute volumes representative of the requirements of clinical practice.

The hyperbaric performance of the Servo 900C in volume preset mode has been previously reported. When using synchronised intermittent mandatory ventilation (SIMV) mode, this ventilator operates using a flow servo loop, which functions by measuring actual gas flow from the inspiratory flow transducer (a screen-type pneumotachometer).[4] The ventilator compares this volume with the preset inspiratory MV chosen by the operator. When actual flow does not match the preset inspiratory MV, electronic control opens or closes a ‘scissors style’ inspiratory flow control valve to provide an adjustment of the gas flow and consequent volume delivery.

A specific failing of the pneumotachometer type of flow sensor is that the output signal of such sensors is sensitive to pressure and, unless there are electronic systems present to compensate for this, gas delivery becomes increasingly inaccurate as the ambient pressure rises.[3,5,6] Our hyperbaric unit regularly uses the Servo 900C ventilator and we therefore undertook further investigations in this area.

Research methods and materials

As an equipment performance study not involving research subjects, there was no requirement for ethics committee approval. The hyperbaric chamber used was a clinical, multiplace, three-compartment unit (Fink Engineering, Melbourne).[7]

The MV delivered by the ventilator was measured at ambient pressure of 101.3 kPa and at 283 kPa. Where delivered MV was less than the set MV, the set MV was increased incrementally to discover what correction value was necessary to compensate for the shortfall. During testing the ventilator was operated with a test lung (Siemens test lung 190®), which was attached to the ventilator's patient circuit to approximate normal physiological resistance.[8]

Delivered MV was measured by timed collection of output from the exhaust valve of the ventilator. Exhaust gas was collected via a low-resistance system (Figure 1) incorporating a three-way, manual, directional control valve for gas diversion (Hans Rudolph, Missouri, USA) and a Douglas collection bag (Vacumed, California, USA). Volume was measured with a two-litre calibration syringe (A-M Systems Inc, Carlsborg, Washington). A vacuum pressure gauge was also incorporated into the bag to facilitate consistent emptying of the collection bag prior to each measurement.

A single Servo 900C ventilator was used for the study (Figure 2). The machine had undergone 277 hours of hyperbaric use since the last service but prior operational hours were unknown. During the course of data collection no servicing was required. Data were collected whilst operating the ventilator in SIMV mode.

RESEARCH PROCEDURES

The ventilator settings chosen for testing purposes were considered typical of starting-point ventilatory parameters and consistent with literature reports.[9,10] These were:

- respiratory rate of 10–20 breaths per minute
- pressure support of 12 cmH_2O
- positive end expiratory pressure (PEEP) of 5 cmH_2O
- 100% oxygen

Figure 2
The Servo 900C ventilator

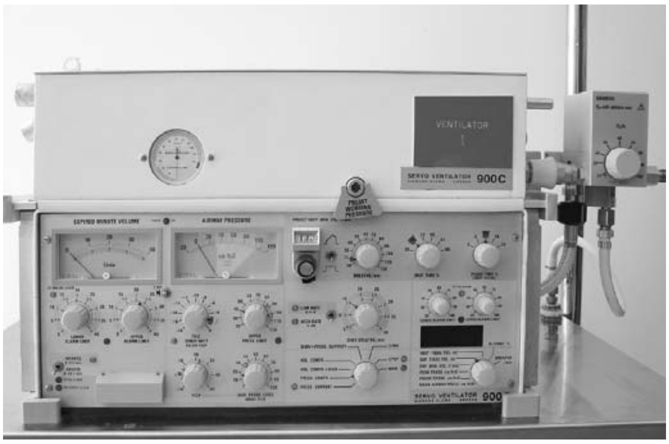
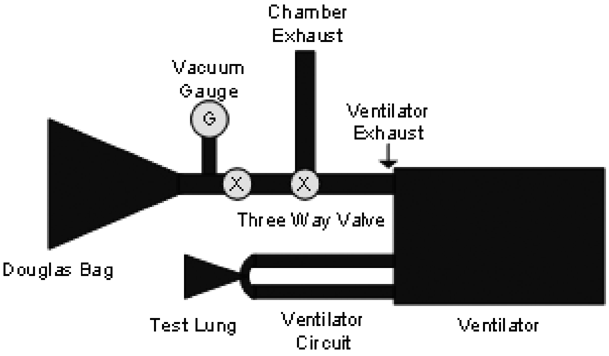


Figure 1
Collection circuit used to measure delivered minute volume



Minute volumes of 1.0, 10 and 15 $L.min^{-1}$ were chosen to span the range of paediatric, normal adult and large catabolic adult volumes.

Prior to data collection the ventilator was set up in accordance with normal practice. Air from the collection bag was evacuated prior to each measurement with the measuring syringe. A vacuum was confirmed to be present on the gauge prior to advancing the syringe to zero pressure. This ensured consistent removal of all air from the collection bag and that there were no leaks in the system.

The ventilator was set to the desired respiratory rate. The Siemens Servo 900C ventilator has a lid which can be opened to allow observation of the 'scissors style' valves that control inspiratory and expiratory flow. The operator timed the actual respiratory rate and made fine adjustments to the ventilator's rate setting as needed to ensure that exactly one minute elapsed from opening of the respiratory scissors valve to the closing of the expiratory valve after the desired number of ventilation cycles.

The procedure for MV collection was to open the three-way valve into the collection bag when the ventilator's expiratory valve closed at the beginning of inspiration. Upon closure of the expiratory valve after the last breath and one minute later the three-way valve was closed to the collection bag. The graduated calibration syringe was then used to evacuate the volume of the collection bag until a negative pressure was recorded on the vacuum gauge. The syringe was then advanced until a zero pressure reading was obtained on the vacuum gauge. The operator then recorded the volume on a data collection sheet.

SAMPLE SIZE

For each ventilator setting, measurement was performed 20 times at sea-level pressure and 20 times at a pressure of 283 kPa. Prior to analysis of the data, an examination of the underlying distribution was undertaken. Two independent operators collected and measured volumes using the same technique to test for the possibility of operator technique error.

Results

All data were analysed using SPSS® v13.0. The examination of data distribution suggested that data for each ventilator setting and pressure condition were approximately normally distributed, and parametric tests were used (Fisher's and Pearson's skewness coefficients were 1.96 and 0.50 respectively).[11–13] Comparisons between set and delivered MV were therefore conducted using independent t-tests.

RELIABILITY OF OPERATOR TECHNIQUE

There was no statistically significant difference in the volumes collected by different operators ($t = -1.14$, df $=15.12$, $P = 0.27$).

MINUTE VOLUMES DELIVERED

There was a significant reduction in actual delivered MV at 283 kPa for all set MVs (Table 1). At the nominally typical high, but not extreme, adult ventilation MV setting of 10 $l.min^{-1}$, the ventilator actually delivered 9.55 $L.min^{-1}$ at 101.3 kPa and 6.53 $l.min^{-1}$ at 283 kPa (95% CI 2.97–3.00, $P < 0.01$).

CORRECTION VALUES TO COMPENSATE FOR UNDER DELIVERY

In an attempt to identify an appropriate correction factor, the ventilator's set MV was progressively increased with the aim of achieving delivery of the desired MV. An MV setting increase of 0.7 $L.min^{-1}$ was required to achieve a desired MV of 1 $L.min^{-1}$ at 283 kPa. However, for the set MVs of 10 $L.min^{-1}$ and 15 $L.min^{-1}$ the maximum MV achievable at 283 kPa was approximately 9.25 $L.min^{-1}$.

Even adjusting the MV by +25 $L.min^{-1}$ above the set MV of 1 $L.min^{-1}$ (Figure 3) or increasing the set MV to the ventilator maximum of 99.9 $L.min^{-1}$ (Figure 4) did not raise the maximum delivered MV above a plateau short of the desired MV for settings of 10 and 15 $L.min^{-1}$.

Discussion

Although it was designed over 20 years ago, the Servo 900C is a moderately sophisticated ventilator, which has been extensively used in the intensive care setting. It remains one of the most advanced HBOT-compatible ventilators given its multiple modes of ventilation, including continuous

Figure 3
Effect of increases in set minute volume (MV) on delivered MV at 283 kPa (baseline set MV = 1.0 $L.min^{-1}$)

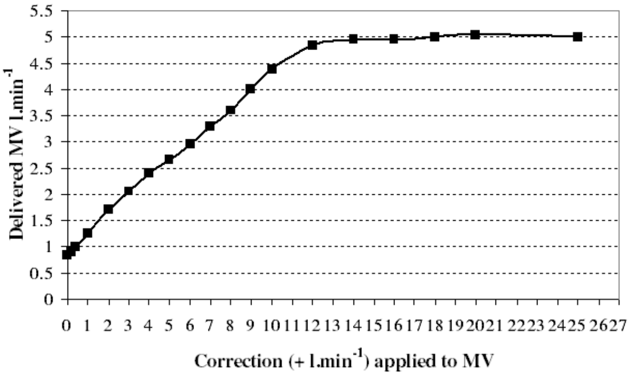


Figure 4
Effect of increases in set minute volume (MV) on delivered MV at 283 kPa (baseline set MV = 10 $L.min^{-1}$)

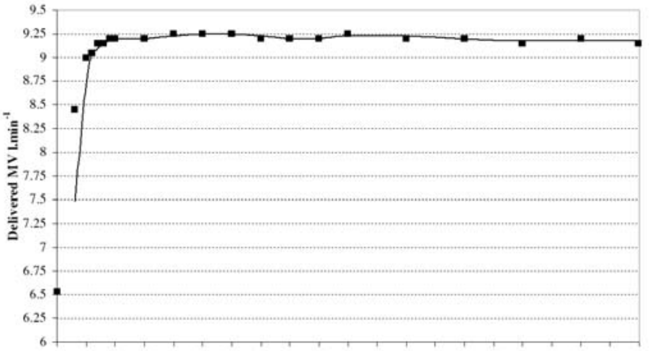


Table 1
Delivered minute volume at 101.3 kPa and 283 kPa relative to set minute volume (MV)

Pressure (kPa)	Number of readings	Set MV ($L.min^{-1}$)	Mean delivered MV ($L.min^{-1}$)	Standard deviation	P value	95% CI
103	20	1	1.03	0.025	< 0.01	0.17–0.20
283	20	1	0.84	0.022	< 0.01	0.17–0.20
103	20	10	9.55	0.040	< 0.01	2.97–3.00
283	20	10	6.53	0.070	< 0.01	2.97–3.00
103	20	15	14.5	0.050	< 0.01	5.34–5.43
283	20	15	9.12	0.070	< 0.01	5.34–5.43

mandatory ventilation (CMV), synchronised intermittent mandatory ventilation (SIMV), pressure control ventilation (PCV), continuous positive airway pressure (CPAP) and pressure support (PS).[14,15]

Literature on the use of this ventilator within hyperbaric settings remains sparse. Some studies have demonstrated that raised ambient pressure in a hyperbaric chamber may cause disparity between displayed and delivered tidal volume (TV) and MV, with a reduction in the volumes actually delivered compared with those set.[3,5,15]

A recent study involving a range of ventilators including the Servo 900C is one of the more scientifically rigorous to date, with the measurement apparatus detailed and methodology clearly outlined.[3] In this study each ventilator was tested at 101.3, 131, 161, 192, 283 and 608 kPa. The ventilator settings for testing were reported to be a TV of 750 ml, an inspiration/expiration (I:E) ratio of 1:2, and respiratory rates of 10, 15 and 20 breaths per minute. These settings were tested in both SIMV and (if available) PCV modes.

The study results noted a decrease of TV in SIMV mode as ambient pressure rose, a change attributed to the increasing gas density at raised ambient pressure. The MV and TV shown by the ventilator's digital displays were higher than the actual delivered volumes, consistent with our observations from clinical practice. In order to compensate for this, the authors reported increasing the delivered volumes to achieve the preset values but no correction values were cited. The conclusion was that although alteration of function occurs this could be accommodated and constant ventilation achieved, although at higher atmospheric pressures compensation was limited due to the range of the ventilator.

These results were consistent with a previous study on the Servo series of ventilators, which reported one set of data in the hyperbaric environment.[5] In this study the ventilator was set to deliver 10 L.min^{-1} at 101.3 kPa and actually delivered only 6 L.min^{-1} at 283 kPa. It also reported that the ventilator's digital displays of delivered MV read artificially high values at pressure as a consequence of the pneumotachometer flow sensor. The investigators claimed to have increased MVs to achieve the original settings and reported operation of this ventilator for hundreds of hours without malfunction, but no information was provided with respect to the correction factors necessary or the maximum volumes able to be delivered.

The results of our study are consistent with previous findings, showing significant differences between the delivery of MV at ambient pressure and at 283 kPa for set MVs of 1.0, 10 and 15 L.min^{-1}.[3,5,15] The reduction in MV delivered at 283 kPa was clinically significant – enough to require correction to achieve results closer to the desired MV. The particular maximum output we identified (approximately 9.5 L.min^{-1}) is probably specific to the rate, pressure support, PEEP and I:E ratio settings we chose for the study. However, it is clear that the ventilator has output limitations at pressure in the SIMV mode that can be clinically important. Such deviations of delivered MV from the set MV may represent a threat to the patient through hypoxia and/or hypercarbia.

As mentioned in the introduction, a specific failing of the pneumotachometer type of flow sensor is that the output signal of such sensors is sensitive to pressure and, unless there are electronic systems present to compensate for this, gas delivery becomes increasingly inaccurate as the ambient pressure rises.[3,5,6]

Whilst it is possible to fully compensate for the reduction in delivered MV at 283 kPa when a set MV of 1 L.min^{-1} is desired, and near compensate for a MV of 10 L.min^{-1}, the latter setting appears to represent an output plateau for this ventilator at this pressure. This may be clinically relevant in the case of large patients or those with respiratory or catabolic (e.g., septic) complications and/or injury.[16] Strategies to slightly raise delivered MV in this mode may include an increase in respiratory rate, and lengthening of the inspiratory period, although the latter carries a theoretically increased risk of gas trapping and barotrauma on chamber depressurisation. Reducing pressure support or PEEP is unlikely to be desirable in a patient requiring large MV ventilation.

Some investigators have suggested that MV delivery in the Servo 900C ventilator is less affected at raised atmospheric pressure when in PCV mode rather than the volume-control mode of SIMV,[3] and it is our clinical practice to change to PCV if ventilation in SIMV mode proves inadequate.

It may be that use of PCV mode should be encouraged during HBOT. However, patient–ventilator synchrony and patient comfort are usually better if one does not change ventilation mode in the case of minimally sedated patients being ventilated in SIMV mode in the intensive care unit. Other problems that can be associated with the PCV mode include higher peak inspiratory pressures, which may be associated with pulmonary barotrauma, plus an increase in mean airway pressure, which can lead to an increase in right ventricular afterload, decreased cardiac preload and reduced cardiac output requiring inotropic support and/or fluid volume loading.[17]

Conclusions

It is possible to utilise the Servo 900C ventilator in SIMV mode in hyperbaric chambers by increasing the set MV with pressurisation in order to maintain delivery of the desired MV. However, the ventilator has a maximum output that may limit its usability in this mode of ventilation. The ventilator's displays of delivered volumes will be above the actual delivered volumes, which should therefore be measured with an independent, pressure-calibrated volumeter or flowmeter. At 283 kPa the ventilator tested demonstrated a maximum deliverable MV of approximately 9.5 $L.min^{-1}$ with pressure support of 12 cmH_2O and PEEP of 5 cmH_2O.

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International Life Saving World Drowning Report 2007

The International Life Saving Federation (ILF) World Drowning Report was presented at the World Water Safety Conference in Portugal recently. The following are excerpts from that report.

The World Health Organisation (WHO) noted that drowning is the third leading cause of unintentional death globally after road traffic injuries and falls (World Health Report 2004)

New Zealand has the third highest drowning toll at 3.3 per 100,000 population in the world, behind Brazil (3.5) and Finland (3.4). Australia is sixth highest (1.5).

ILS data identified key groups or locations most susceptible to drowning:
- Children under five years (and adults, 18–49 years)
- Gender (male)
- Place of occurrence (rivers, lakes, oceans and creeks)
- Climate conditions (low temperature)
- Safety equipment (no lifejacket)
- Use of alcohol (for men when boating and swimming)
- Parental supervision (lack thereof for young children)

Most reports on drowning injury note the difficulties and unreliability of data collection in developing countries.

New Zealand was again noted for the accuracy of its drowning data along with the ease with which they are collected.

The ability to develop drowning prevention initiatives from reliable evidence is critical to reducing the incidence of drowning over time, something that has unquestionably occurred in New Zealand since 1980 from when detailed fatal drowning data have been recorded.