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Performance of the Sechrist 500A Hyperbaric Ventilator in a Monoplace Hyperbaric Chamber

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Weaver LK, Greenway L, Elliott CG. Performance of the Sechrist 500A hyperbaric ventilator in a monoplace hyperbaric chamber. J Hyper Med 1988; 3(4):215–225.—In our initial use of the Sechrist 500A hyperbaric ventilator operating within a Sechrist 2500B monoplace chamber, we observed that the patient's tidal volume (VT) decreased as chamber pressure (P_{CH}) increased more than −10%, the maximum allowable decrement in VT from the ambient VT (500A operator's manual). Therefore we decided to quantitate this decrement in VT and to determine what variables were important for the ventilator to deliver an adequate VT. The 500A ventilator was set up within the chamber in the manner described by the 500A operator's manual. First, an adult Boehringer spirometer was calibrated over the range of monoplace P_{CH} (0.85 to 2.9 ATA at our altitude). This was accomplished by collecting a volume of gas at various P_{CH}, then measuring the volume of gas at atmospheric pressure and calculating the true VT. Comparing measured VT to true VT, the percent error discrepancy was: −1.5, +2.4, +2.8, +6.1, +6.0% at P_{CH} = 0.85, 1.5, 2.0, 2.5, 2.9 ATA, respectively (the + values mean that the spirometer underestimates the actual VT by that %). Once the spirometer calibration was known, we varied the static compliance (C_L = 15 to 8.7 cc/cmH_2O) of a test lung and ventilator control module inlet pressure (P_{IN}) from 55 to 85 psig (the allowed range of P_{IN} by Sechrist) and measured VT as the dependent variable. We found that VT is a function of C_L, P_{CH}, and P_{IN}. Even with a normal C_L, VT decreased more than −10% when P_{CH} exceeded 1.5 to 2.0 ATA. With a C_L = 15 cc/cmH_2O, P_{CH} = 2.5 ATA, and P_{IN} = 55 psig, VT was reduced 38% from that at ambient pressure. We recommend monitoring VT continuously during mechanical ventilation of patients in a monoplace hyperbaric chamber with a hyperbaric-calibrated spirometer, making appropriate ventilator adjustments to maintain an adequate VT.

hyperbaric oxygen, hyperoxygenation, mechanical ventilation, hyperbaric ventilation

Introduction

Most hyperbaric treatments provided to patients in the United States are delivered within monoplace hyperbaric chambers (1). Many of the conditions approved to receive hyperbaric oxygen (HBO) therapy (2) occur in critically ill, mechanically ventilated patients. If these patients are to receive HBO in a monoplace chamber they must be mechanically ventilated with a ventilator either adapted to or designed for use within the monoplace hyperbaric environment. The Sechrist 500A hyperbaric ventilator was designed to be used in the monoplace hyperbaric chamber (3). It has been in use since 1979. According to Sechrist, Inc., there are presently 123 500A hyperbaric ventilators in use (personal communication, May 1987).

It is important to prevent hypercarbia during hyperbaric treatment. Hypercarbia potentiates CNS oxygen toxicity (4), and acidemia may ensue if the arterial partial pressure of carbon dioxide (Pa_{CO_2}) increases (5). Since CO_2 production remains nearly constant, minute ventilation is the major determinant of Pa_{CO_2}. Thus, prevention of hypercarbia requires that tidal volume (VT) and ventilatory rate (VR) remain nearly constant as pressure increases in the monoplace chamber.

The Sechrist 500A ventilator operator's manual states: "As the chamber is pressurized, the control module automatically adjusts the delivery pressure to maintain the preset tidal volume (VT) within ±10%. Inhalation and exhalation times remain unaffected" (3). During our initial use of this ventilator with an intubated, mechanically ventilated patient we observed that the VT decreased markedly as chamber pressure (P_{CH}) increased. This was due in part to a sticking venturi valve, which we have reported previously (6). However, even with a nonsticking venturi valve we observed that VT decreased as P_{CH} increased. Therefore we decided to study the performance of this ventilator. We addressed the following questions:

1. How accurate are spirometers at measuring VT in the HBO environment?
2. What is the relationship between VT and P_{CH}?
3. Is the delivered VT a function of lung compliance (C_L)?
4. Is the delivered VT a function of ventilator control module inlet pressure (P_{IN})? If so, what is (are) the optimal pressure(s)?

Materials and Methods

The Sechrist 500A hyperbaric ventilator was set up within a Sechrist monoplace hyperbaric chamber (type 2500B) in the manner described in (3). Ventilatory rate was set at 15 breaths/min by adjusting expiratory time. The ambient VT was adjusted to 500 to 800 cc by adjusting inspiratory time and flow. An adult mechanical spirometer (#8800, Boehringer, Wynnewood, PA) was placed on the expiratory limb of the circuit. A test lung (Manley Lung Ventilator Performance Analyzer, Medical Developments, Ltd, Chesham, Bucks, England) for lung C_L = 15 and 32 cc/cmH_2O or two 3-liter anesthesia bags (3-liter Breathing Bag, Anesthesia Associates, Inc., San Marcos, CA) connected in parallel (for lung C_L = 61 and 87 cc/cmH_2O) were attached between the inspiratory circuit and the expiratory circuit. Airway resistance was set at zero, and C_L varied. The standard Sechrist breathing circuit was employed (tubing compliance is 2.2 cc/cmH_2O).

To validate the accuracy of the Boehringer spirometer (3-min collection time, VR = 15/min, VT = 700 to 1050 cc at 0.85 ATA) a volume of gas was collected at each data point (0.85, 1.5, 2.0, 2.5, 2.9 ATA, respectively) in a Douglas bag (Warren E. Collins, Inc., Braintree, MA), which was connected to the exhalation port of the spirometer via a one-way valve. With inspiration, O_2 flowed into the test lung. With exhalation, O_2 flowed through the spirometer and was collected in the Douglas bag. At the completion of the O_2 collection the chamber was decompressed. The gas volume was then measured (ATPS) in a 120-liter chain-compensated Tissot gasometer (Warren E. Collins, Inc.). Through the application of Boyle's Law (pressure × volume = constant) the volume of gas at each chamber pressure was calculated. The VR was known so that VT could be calculated. This value was compared to the volume measured by the Boehringer spirometer. Each collection of gas was performed 3 times and was reproducible. Once the accuracy of the Boehringer spirometer was known it was the only spirometer used throughout the remaining data collection.

The hospital's biophysics department validated accuracy of the chamber pressure gauge. A thermistor (Yellow Springs Instrument Co., Yellow Springs, OH, model 700) was passed through an i.v. pass-through port (after fashioning an appropriate seal), allowing the measurement of temperature in the distal airway (in the Sechrist 500A ventilator block). Temperature was read off a Marquette Monitor (Marquette, Inc., Milwaukee, WI).

To answer the question, "How does VT change as P_{CH} varies?", the VT was calculated by measuring the volume delivered by the ventilator through the circuit used in the spirometer calibration, for 1 min divided by the VR. We chose to perform this same data collection with test lung settings of varying lung compliances (15, 32, 61, and 87 cc/cmH_2O), with zero airway resistance over a range of P_{IN}'s.

To see the effect of varying P_{IN} on ventilator performance, a 2-stage variable oxygen regulator (Harris oxygen 2-stage regulator, model 25-100, Harris Calorific Co., Cleveland, OH) was attached to a standard oxygen cylinder ("H" cylinder). The Sechrist 500A ventilator operator's manual states that a pressure of 70 psi gauge ± 10 psig should be used. On the back of the ventilator control module it is stamped "use 60 psig ± 5 psig." Therefore, we elected to test ventilator performance over a range of pressures from 50 to 85 psig using the same previously tested lung compliances (15, 32, 61, and 87 cc/cmH_2O).

Before and after each test we inspected the venturi valve to ensure that it was not sticking.

Results

The accuracy of the Boehringer spirometer that we used for the entire set of data collection in this study is shown in Table 1 (for VTs between 700 and 950 cc at atmospheric pressure). As chamber pressure increases, the spirometer underestimates VT up to a maximum of 6.1% at 2.5 ATA.

Table 1: Calibration Error of a Boehringer Spirometer over a Range of Hyperbaric Pressures

Chamber Pressure, ATA	Percent Error
0.85[a]	−1.5
1.5	+2.4
2.0	+2.8
2.5	+6.1
2.9[b]	+6.0

The + symbol means that the Boehringer spirometer underestimates the actual VT.

[a] Salt Lake City, Utah, is at an altitude of 1341 m above sea level. [b] This is the chamber pressure limit at 1341 m.

The temperature in the ventilator block increased <3°C with chamber compression to 2.9 ATA. This gives <1% change in volume, so this calculation was excluded from the spirometer validation.

Table 2 displays the data. At each P_{CH}, VT is listed for each P_{IN} and C_L tested. Figure 1 shows the percent change in VT (ΔVT) plotted against P_{CH} for C_L = 1.5 and 87 cc/cmH$_2$O, which represent the extremes of the test. The *broken* and *solid* lines, respectively, define the range of VTs over the range of P_{IN} tested. Clearly, VT is a function of P_{CH}, P_{IN}, and C_L. The greatest ΔVT occurred with the lowest P_{IN}, the lowest C_L (stiffest lung), and at the highest P_{CH}. Increasing P_{IN} at the higher P_{CH} (>1.5 ATA) decreased the Δ VT.

Figure 2 shows ΔVT as a function of P_{CH} and C_L, holding P_{IN} constant at 70 psig (the recommended P_{IN}). When P_{CH} exceeds approximately 1.5 ATA, the ΔVT is greater than −10% for all C_L tested, although the least ΔVT is with the highest C_L.

We observed that the time required to deliver a preset VR (t_v) depends on P_{IN} as well (Fig. 3). The volume of gas ventilated during 1 min was measured. As we decreased P_{IN} we observed that VR also decreased (the control module knobs were not adjusted during each change in P_{IN}). VR was set to 15 breaths/min at a P_{IN} equal to 70 psig at 0.85 ATA. The ordinate shows that the time required to deliver 15 breaths as P_{IN} varied. We noted that more time was required to deliver the 15 breaths as P_{IN} was decreased. By measuring inspiratory and expiratory time (by graphing airway pressure as a function of time), we found the major component of the above change was a change in expiratory time (Fig. 4). VR was not affected by changing P_{CH} if P_{IN} was constant.

The performance of our ventilator was verified as acceptable by Sechrist, Inc. (letter, 3 September 1987). A second ventilator was also tested in the same manner. It performed identically to the first ventilator with the exception of a C_L = 16.7 cc/cmH$_2$O, where the ΔVT was even more markedly increased at P_{CH} >1.5 ATA and when P_{IN} <75 psig.

Table 2: Tidal Volumes Tabulated as Function of Chamber Pressure, Control Module Pressure and Compliance

		V_T cc[a]			
P_{CH}, ATA	P_{IN}, psig	C_L = 87[b]	C_L = 61	C_L = 32	C_L = 15
0.85	85	788	919	804	1070
	80	796	945	822	1067
	75	816	950	833	1067
	70	833	968	843	1067
	65	841	980	849	1061
	60	922	995	858	1064
	55	926	1022	867	1063
1.00	85	780	880	769	1019
	80	790	903	783	1022
	75	790	911	793	1034
	70	800	928	802	1019
	65	810	943	811	1031
	60	840	956	819	1020
	55	850	977	827	1029
1.50	85	737	780	710	943
	80	727	811	726	947
	75	737	828	735	951
	70	763	839	742	953
	65	768	852	753	955
	60	768	868	761	957
	55	788	814	768	955
2.00	85	699	719	673	903
	80	709	752	691	901
	75	709	774	697	904
	70	720	784	709	904
	65	730	794	715	903
	60	730	801	720	836
	55	720	791	706	790
2.50	85	711	717	672	903
	80	711	748	681	903
	75	711	754	684	892
	70	721	761	695	831
	65	690	746	671	778
	60	690	688	608	711
	55	637	625	541	639
2.90	85	700	696	720	884
	80	689	718	660	845
	75	689	714	646	782
	70	678	667	595	727
	65	647	613	537	662
	60	572	551	473	592
	55	498	474	395	513

[a] All V_T are corrected by the spirometer error (Table 1); [b] cc/cmH_2O.

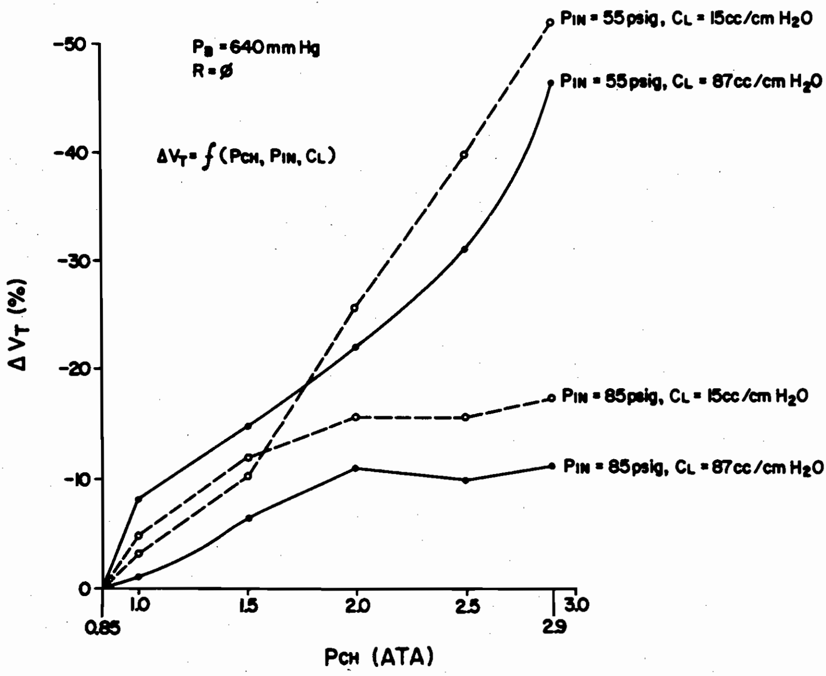

FIG. 1—The percent change in ΔVT is plotted as a function of P_{CH} for C_L 15 and 87 cc/cmH_2O. *Broken* and *solid lines* represent 2 families of curves defined by the ventilator P_{IN}. Although not depicted, the ΔVT for C_L = 32 and 61 cc/cmH_2O fall within the boundaries shown here. Barometric pressure (PB) is as shown. Airway resistance (R) = 0.

Discussion

With a normal functioning venturi valve the ability of the Sechrist 500A hyperbaric ventilator to deliver the preset (atmospheric) VT is a function of chamber P_{CH}, C_L, and P_{IN}. The variability of VT is significant. For example, assume one is mechanically ventilating a patient with adult respiratory distress syndrome (ARDS) who requires hyperbaric therapy. If we assume C_L = 15 cc/cmH_2O and P_{IN} = 55 psig, a preset VT of 1050 cc would be reduced to a VT of 650 cc at a chamber pressure of 2.5 ATA. This represents a reduction of 38% in the preset VT. If the VR is not concomitantly increased (assuming no change in CO_2 production and ventilatory dead space), the alveolar ventilation would also fall 38%, allowing the Pa_{CO_2} to increase. This could result in two untoward effects: CNS oxygen toxicity (4) and acidemia (5) due to respiratory acidosis.

This example may be a worst-case scenario, but it is not unreasonable to expect patients with stiff lungs to occasionally require HBO therapy. Many of the approved indications for HBO therapy may be associated with a low C_L

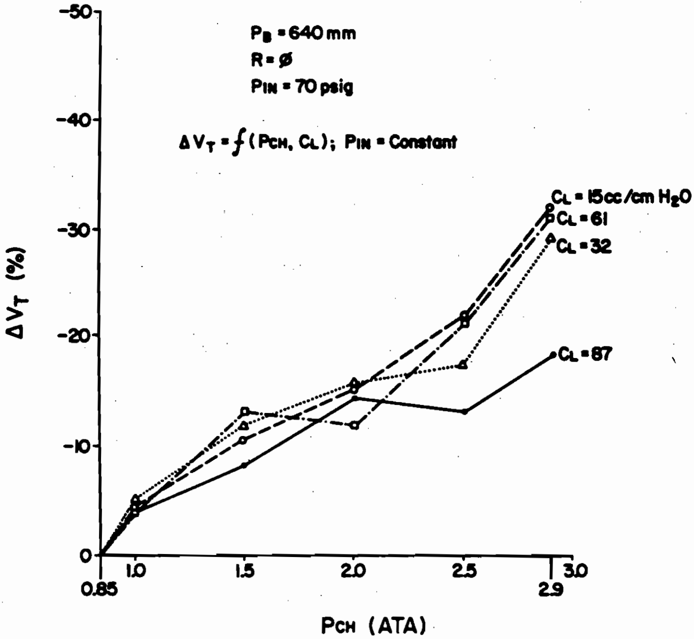

FIG. 2—ΔV_T plotted against P_{CH} with P_{IN} held constant at 70 psig for varying C_L. ΔV_T exceeds −10% for all lung C_L tested when P_{CH} is greater than approximately 1.5 ATA.

(e.g., gas gangrene with ARDS, carbon monoxide poisoning with smoke inhalation injury, acute crush injury with chest or lung contusion or aspiration). Even with a normal C_L the V_T decreased greater than 10% when P_{CH} exceeded 1.5 ATA.

With stiff lungs (C_L <30 cc/cmH_2O) and at the higher P_{CH} (>2.0 ATA), the ability of the Sechrist 500A ventilator to deliver a high minute ventilation ($\dot{V}_E$) is limited. If one is treating a patient who requires a high $\dot{V}_E$ (for example, 15 liter/min) to maintain an adequate pH with a low C_L, the 500A may be unable to deliver that $\dot{V}_E$ even by increasing P_{IN} to 85 psig at a P_{CH} much over 2.0 ATA. Chamber pressures between 2.0 and 2.8 ATA are required for most of the disorders for which HBO is indicated (2).

With the marked reduction in V_T that occurs with low compliance lungs at high P_{CH}, the operator of the ventilator may be tempted to increase V_T by increasing inspiratory time. Likewise, the operator may increase $\dot{V}_E$ by increasing VR. Both of these maneuvers should be done cautiously as the patient may "stack breaths," which could result in intrathoracic gas trapping. Major adverse hemodynamic consequences could ensue as well as pulmonary overpressurization and barotrauma if there is inadequate exhalation time (7–8).

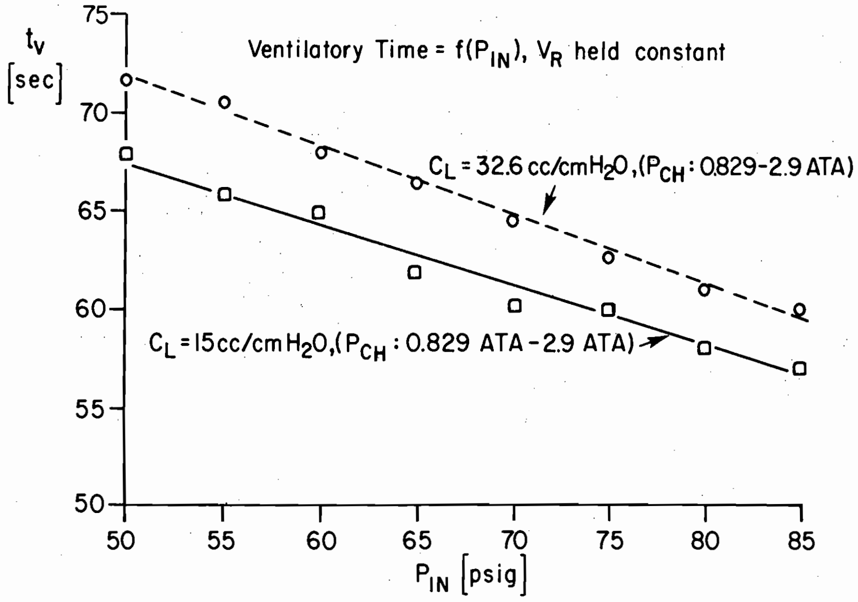

FIG. 3—Ventilatory time (t_v) as a function of Sechrist 500A hyperbaric ventilator control module P_{IN}. VR was set at 15 breaths/min with P_{IN} = 70 psig (C_L = 15 cc/cmH_2O). As P_{IN} was varied, the time required to deliver 15 breaths (t_v) also varied. P_{CH} changes did not affect the change in t_v.

Hospital oxygen delivery pressures (at the wall outlet) generally are limited to 50 to 55 psig (9). The 500A ventilator requires a P_{IN} of at least 65 psig and perhaps even up to 85 psig for optimal delivery of a given VT when P_{CH} exceeds 1.5 ATA. Consideration of operating the 500A ventilator at higher than most hospital oxygen delivery (wall) pressures is reasonable. We operate our 500A ventilator with oxygen supplied from H-cylinders with a variable 2-stage regulator used to control P_{IN} (between 70 and 85 psig). The present data suggest that there is a flow-resistive drop in the supply lines that may be hose-orifice diameter dependent. A future experiment could determine if ventilator performance is improved if the oxygen supply line, control module outlet line, and the pass-through fittings are changed to a larger diameter.

Inspiratory and expiratory time also depend on P_{IN}. If P_{IN} remains constant over the operational range of the Sechrist chamber (0.85–2.9 ATA), inspiratory and expiratory time remain constant and the VR does not change. This observation could be important, however, if P_{IN} dropped for any reason during the course of treating a mechanically ventilated patient. Not only does VT change if P_{IN} changes but VR as well. The $\dot{V}E$ (VT × VR) may or may not change, depending on P_{CH}, C_L, and P_{IN}. If the $\dot{V}E$ decreased (which is likely at P_{CH} >2.0 ATA if P_{IN} decreased) there could be an abrupt change in Pa_{CO_2} and pH.

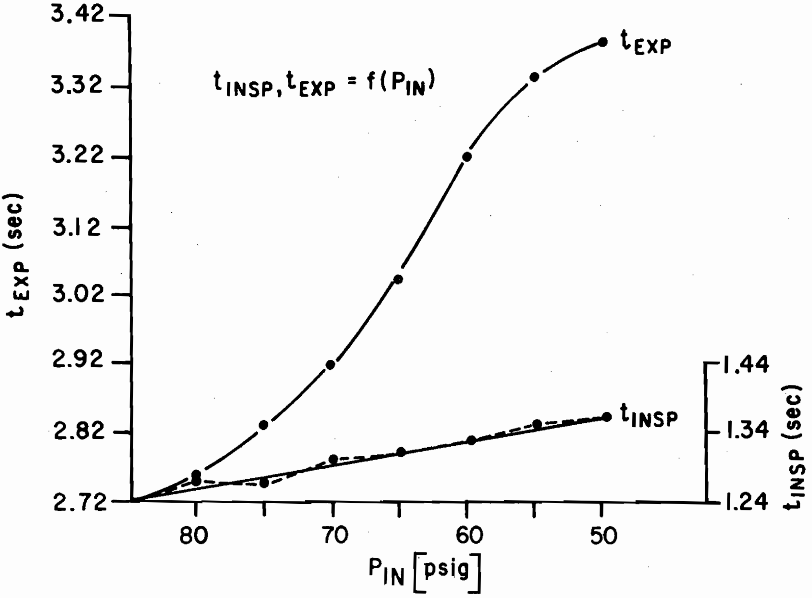

FIG. 4—Inspiratory and expiratory times (t_{exp}, t_{insp}) plotted against Sechrist 500A hyperbaric ventilatory control module P_{IN}. The major determinant of the effect of P_{IN} on VR depicted in Fig. 3 is a change in expiratory time, particularly prominent at the lower P_{IN} (VT = 850 cc at P_{CH} = 0.85 ATA, C_L = 32 cc/cmH_2O).

The present study was performed at an altitude of 1341 m above sea level (0.85 ATA). The lower ambient pressure accounts for some of the reduction in VT that we observed. However, even if we assume the VT measured at 1.0 ATA as our starting VT, VT still fell below the volume calculated by multiplying the VT at 1.0 ATA times 90% when P_{CH} exceeded approximately 2.0 ATA, dependent of course on C_L and P_{IN}. The Sechrist 500A operator's manual does not discuss a possible reduction in VT with chamber pressurization, which may be enhanced with operation of the ventilator at an elevated altitude. We would expect the reduction of VT as P_{CH} increased to be even more marked at altitudes higher than 1341 m. (The slope of ΔVT vs. P_{CH} is fairly steep between 0.85 and 1.0 ATA, *see* Figs. 1–2.)

The Sechrist ventilator tubing has a compliance factor of 2.2 cc/cmH_2O. Therefore the tubing losses will be minimal, even with high-peak airway pressures. If other circuits are substituted that have a higher tubing compliance factor, it may be difficult to deliver an adequate gas volume from the ventilator block to provide the volume lost in the compliance of the circuit and to provide an adequate VT to the patient, particularly, with high-peak airway pressures and at high P_{CH}.

We have presented a method of spirometer calibration within the monoplace hyperbaric environment and have provided the accuracy of our adult Boehringer spirometer. We do not know if other spirometers, or even another Boehringer spirometer, would have the same percent error discrepancy as ours. Kindwall and Goldmann (10) state that a VT measured with a Wright's spirometer can be corrected by specific factors that are a function of P_{CH}. The single Boehringer spirometer we tested exhibited a greater error than what Kindwall and Goldmann describe (−3% at P_{CH} = 3.0 ATA, VT = 1060 cc), underestimating VT as P_{CH} increases. It is likely that this error is not solely due to a change in gas density. If it were, we would expect a percent-error curve linearly dependent on P_{CH} in which the VT (measured by spirometry) would overestimate the actual VT.

This study did not deal with variable airway resistance. Airway resistance was set equal to zero, which clinically is unlikely in intubated patients. Therefore the findings reported here may also apply to patients who exhibit high airway resistance, even if their static lung compliance is relatively normal.

In conclusion, we recommend:

1. Continuously measure VT with a spirometer that has been calibrated to the hyperbaric environment.
2. Continuously monitor P_{IN}.
3. Use a P_{IN} that is at least 70 psig and which can be adjusted up to 85 psig, allowing the ventilator operator to provide a VT closest to the preset VT over the operational range of P_{CH}.
4. Ensure that if P_{IN} falls for any reason during HBO treatment that the VT is appropriately adjusted by manipulating flow or inspiratory time, or both. Also ensure that the VR is adjusted to deliver an adequate minute ventilation while also providing adequate exhalation time.
5. Monitor VT during decompression to maintain an adequate $\dot{V}$E to prevent delivering too large a VT, which could result in pulmonary barotrauma or hemodynamic compromise, or both.
6. Be aware that a patient may stack breaths if an attempt is made to increase VT by increasing inspiratory time. This may be manifested by an increasing peak or end expiratory pressure, or both.
7. Use a ventilator circuit that has a low tubing compliance factor for patients who have high peak airway pressures and a high $\dot{V}$E (demanding a rather large VT) to minimize volume loss in the circuit.

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