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Functioning of ICU ventilators under hyperbaric conditions – comparison of volume- and pressure-controlled modes

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Warning
Intensive care unit (ICU) ventilators are generally designed for use at normal atmospheric pressure and are not approved for use in a hyperbaric chamber at elevated ambient pressures. Any unauthorized use of electrical devices in the hyperbaric chamber is strictly prohibited by law. In fact, it holds the danger of accidents and fire hazards and will potentially cause serious damage to objects and human beings. It is the responsibility of any user to contact manufacturers and technical supervision authorities of his/her own country prior to using any device in the hyperbaric chamber and to inform themselves about precautionary measures and modifications prescribed by law and technical expertise.

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Abstract *Objective*: To evaluate the function of four currently available, not specifically modified time-cycled ICU ventilators (EVITA 4, Oxylog 2000 HBO and Microvent from Drägerwerk, Germany and Servo 900C, Siemens-Elema, Sweden) under hyperbaric conditions using volume-controlled ventilation (VCV) and, if available, pressure-controlled ventilation (PCV).
Design: All ventilators were studied on an electromechanical lung simulator consisting of a motor driven bellows (LS 1500, Drägerwerk, Germany) at normobaric (1 bar) and hyperbaric ambient pressures (1.3, 1.6, 1.9, 2.8 bar). Servo 900C and Microvent were additionally tested at 6 bar.
Settings: Hyperbaric chamber.
Measurements and results: During VCV the tidal volume (V_T) was set at 750 ml at normobaric conditions prior to starting hyperbaric exposure. During PCV the same V_T setting was achieved by adjusting the inspiratory pressure level. At each ambient pressure we registered airway pressure (measured inside the bellows) and flow (derived from the linear displacement of the bellows) for a period of 1 min. From these data we calculated off-line V_T, inspiratory airway peak and plateau pressure (P_{peak} and $P_{plateau}$) and, during PCV only, peak inspiratory flow (V_{max}) and the time delay between onset of and peak inspiratory flow (V_{delay}). During VCV inspiratory flow and, consequently, V_T consistently decreased with increasing ambient pressure. In contrast, during PCV V_T remained stable at each condition despite a slight decrease in V_{max}.
Conclusions: Whenever available, PCV should be preferentially used during hyperbaric oxygen therapy due to the stability of ventilator functioning. Based on the specific ventilator properties at increasing ambient pressures, appropriate corrections should be possible which will allow the safe use of ICU ventilators even during VCV.

Key words Hyperbaric oxygen therapy · Ventilator · Airway resistance · Gas density

Introduction

Several indications for hyperbaric oxygen therapy in intensive care unit (ICU) patients are commonly accepted [1]. Obviously, in these patients the complete intensive care therapy, including mechanical ventilation when necessary, should also proceed under hyperbaric conditions. ICU ventilators, however, are designed for use in a normal atmospheric environment and their function is disturbed at increased ambient pressure. Available data on ventilator functioning in the hyperbaric chamber [2, 3, 4] make it evident that each device behaves differently under such particular conditions. In fact, the function of each specific type of ventilator cannot be

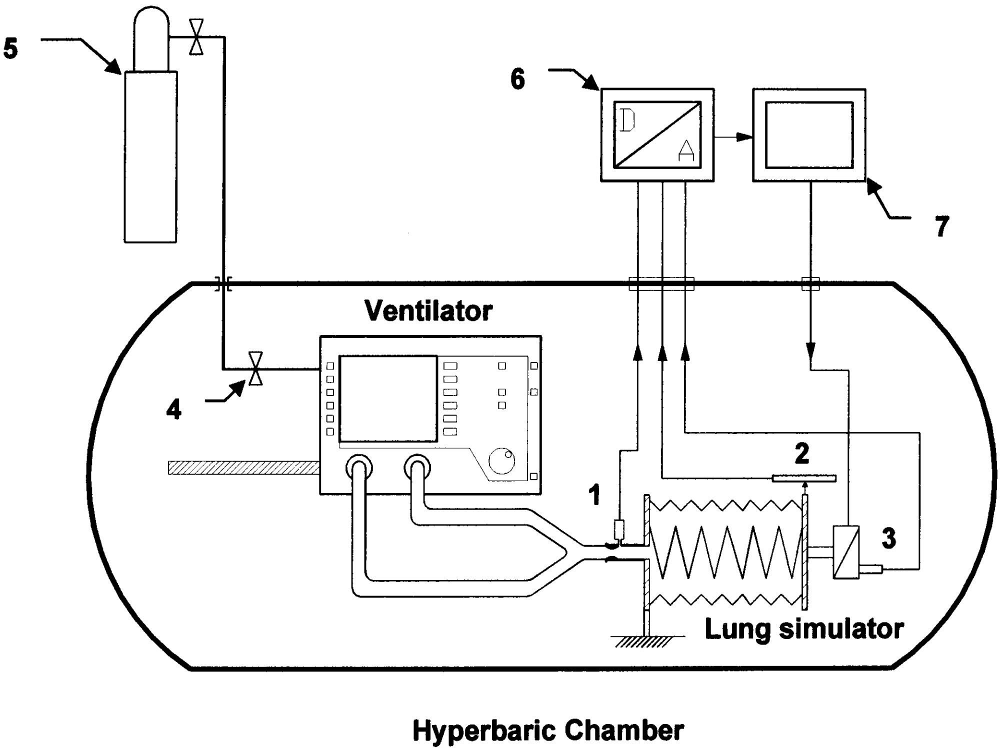


Fig. 1 Schematic diagram of the experimental setup. Both ventilator and lung simulator were placed inside the hyperbaric chamber. The analog outputs of differential airway pressure transducer (1), linear displacement transducer (2) and electromechanical power transducer (3) were transformed by a A/D converter (6) into digital signals and sampled by the data collecting computer (7). This computer was used simultaneously as control unit for the lung simulator. The gas supply for the ventilator (5) was set at 11 bar and provided by the same source used for the breath-in-built system of the chamber. Proximal to the ventilator the supply pressure was adjusted automatically by a further pressure control valve (4) to keep inlet pressure constant at 5.5 bar above ambient pressure

precisely predicted by applying gas laws only without further considering the very specific details of their technical design as well as sophisticated physical models and equations derived from laws of fluid mechanics. Empirical data obtained with each ventilator type, however, allow a simple and accurate description of their functioning under hyperbaric conditions.

The aim of our study was to compare the function of four currently available, not specifically modified time-cycled ICU ventilators under increasing hyperbaric conditions (EVITA 4, Oxylog 2000 HBO and Microvent, Drägerwerk, Germany, and Servo 900C, Siemens-Elema, Sweden). Since the technical designs of these ventilators largely differ in as much as each one of them controls inspired flows by means of specific valve types and algorithms, they should behave differently under hyperbaric conditions. Consequently, their properties at increased ambient pressure have to be studied separately in order to correct accurately for their distorted functioning. All ventilators were tested on an electromechanical lung simulator in volume-controlled and, if available, pressure-controlled mode. Our intention was to characterize the function of each one of the ventilators and to determine to what extent the altered function of the ventilators at increased ambient pressure is monitored correctly by the parameters displayed, i. e. whether the display of the ventilator may potentially mislead the user. Furthermore we propose a simple empirical method to compensate adequately for the effects of hyperbaric exposure in order to guarantee constant ventilatory support regardless of the actual ambient pressure.

Materials and methods

We performed all measurements on the electromechanical lung simulator LS 1500 (Drägerwerk, Lübeck, Germany), which had previously been used for ventilator function tests [5]. This device consists of a motor driven bellows, and the motor driving voltage is provided by the output of a servo-control electronics, which receives input signals from the linear displacement transducer of the bellows, and from the pressure transducer, which senses the pressure inside the bellows. The compliance of the lung simulator, which can be set to values between 5 and 100 ml/cmH_2O by adjusting the gain of the servo loop, was kept constant at 50 ml/cmH_2O throughout the experimental series. The resistance of the bellows at its inlet was 5 cmH_2O × s/l. Prior to starting the experiment series, the output of the linear displacement transducer was calibrated by increasing the volume of the bellows in a stepwise manner using a 3 l supersyringe.

Study design and data sampling

During the experiments the lung simulator and the ventilators were placed inside, and the control and data collecting units outside, the hyperbaric chamber. The gas supply for the ventilator was provided by the same source used for the breath-in-built system of the chamber. Hence supply pressure was continuously adapted to compensate for the increased ambient pressure in order to keep the difference between supply and ambient pressure constant at 5.5 bar. The experimental setup is further explained graphically in Fig. 1.

Each ventilator was tested at five different ambient pressure conditions: 1, 1.3, 1.6, 1.9 and 2.8 bar, Servo 900C and Microvent were additionally tested at 6 bar. EVITA 4 and Servo 900C were studied during both volume- and pressure-controlled ventilation (VCV and PCV), Oxylog 2000 HBO and Microvent with VCV only since PCV is not available in these models. Regardless of the actual mode of ventilation, the ventilator parameters were preset under normobaric conditions to yield tidal volumes (V_T) of 750 ml. The inspiration to expiration time (I:E) ratio was always 1:2. Inspiratory flow was constant during VCV with each ventilator. With this mode, respiratory rates (f) of 10, 15, and 20 breaths/min, which yield different inspiratory flow rates, were tested separately. During PCV we performed two different series of measurements with f = 10 and 20 breaths/min with both the EVITA 4 and Servo 900C ventilators. With the EVITA 4, ventilator inspiratory pressure rise time was set at its minimum (theoretically 0 s) which corresponds to the inherent settings of the Servo 900C. All ventilator settings were kept constant throughout each experimental series, i. e. at each ambient pressure.

With each experimental condition we measured both airway pressure (P_{aw}), by a differential pressure transducer (142 PC 01G, Honeywell, Plymouth, Minn.)which sensed the difference between ambient pressure and pressure inside the bellows, and the actual volume of the bellows, which was obtained from the signal of the linear displacement transducer. Both signals were continuously registered to perform off-line analysis for a duration of 60 s with a sampling rate of 100 Hz on a personal computer using the DaqBoard 216 A/D converter system (IOtech, Cleveland, Ohio) and the data acquisition software DASYlab (Datalog, Mönchengladbach, Germany). Flow was calculated online by differentiation of the volume signal and stored on a separate channel of each data file.

The values of V_T (obtained from minute ventilation divided by respiratory rate with the Oxylog 2000 HBO and the Microvent) and peak and plateau inspiratory pressures (P_{peak} and $P_{plateau}$) displayed by the ventilators were noted with each experimental condition simultaneously with the digital data acquisition.

Calculations

Calculations were performed off-line using a self-developed computer program [6]. This software first subdivides each registration into separated respiratory cycles by determining the beginning of each inspiration and of the subsequent expiration according to the flow curve. Then the parameters of interest were obtained breath-by-breath as follows: V_T as the volume of the bellows at the beginning of each expiration, P_{peak} as the maximum P_{aw} during inspiration, $P_{plateau}$ as the P_{aw} at the end of the inspiratory breath hold period (EVITA 4 and Servo 900C only), peak inspiratory flow (V_{max}) as the maximum flow value during inspiration and V_{delay} as the time lag between inspiratory flow onset and V_{max}. The two latter variables were of relevance during PCV only.

Data analysis

We analyzed V_T, P_{max} and $P_{plateau}$ obtained during VCV by comparing the values measured at the different ambient pressures and by subsequently comparing them with the values displayed by the ventilators. The data obtained during PCV under incremental ambient pressures were also analyzed by comparing measured and displayed V_T values. Furthermore we compared V_{max} and V_{delay} obtained under the different study conditions. Finally, we developed strategies to compensate for the altered functioning of the ventilators under hyperbaric conditions; these will be presented in the following section together with the experimental results.

Results

Original curves registered using VCV and PCV at different ambient pressures are shown in Figs. 2 and 3. The results obtained during each study condition are summarized in Tables 1 (VCV) and 2 (PCV).

During VCV, V_T continuously decreased with increasing ambient pressures regardless of the actual inspiratory flow. At the same time, the V_T value displayed by the ventilator slightly decreased with the Servo 900C, and was approximately constant with the ventilators EVITA 4, Oxylog 2000 HBO and Microvent. Consequently, the V_T on the display of these ventilator types progressively overestimated the true value. In contrast to V_T, the P_{peak} and $P_{plateau}$ values measured with the lung simulator and displayed by the ventilator were almost identical. However, both airway pressure parameters decreased with increasing ambient pressure as a result of the changes in V_T.

During PCV, V_T was stable but V_{max} decreased and V_{delay} increased with increasing ambient pressure regardless of the respiratory rate (Table 2). The duration of inspiration was constant within each experimental series. These results are further documented by Fig. 3 which confirms the stability of V_T and the flow changes. In fact, the flow curve was broadened under hyperbaric conditions.

Based on our experimental data we attempted to adjust the ventilator settings in order to achieve stable values at each ambient pressure. This procedure is shown in Fig. 4. Basically it simply consists of presetting higher V_T values as estimated from the relative decrease of V_T under hyperbaric, when compared to normobaric, conditions. By doing so it was possible to compensate for the V_T decrease up to 0.9 bar. At pressure values up to 2 bar, however, V_T could not be fully compensated for because, for the given V_T, the range of the ventilators was too small to permit an adequate setting.

Discussion

This investigation was carried out to study how the functioning of currently available ICU ventilators is altered under hyperbaric conditions. The main results, which will be discussed in this section, are (1) Regardless of the ventilator tested, their functioning is widely altered during VCV in as much as inspiratory flow, and consequently V_T, consistently decreased with increasing ambient pressure. These changes are quantitatively specific

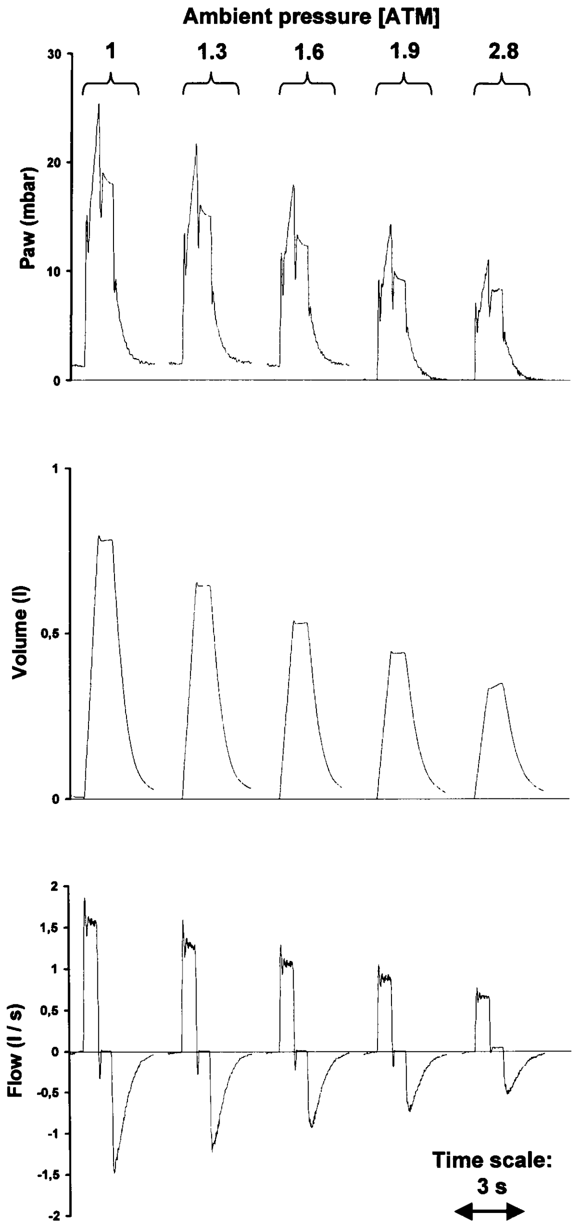


Fig. 2 Original registrations representing airway pressure, inspired volume and flow of single inspirations during volume-controlled ventilation at different ambient pressures with the ventilator EVITA. The five breaths represent data at 1, 1.3, 1.6, 1.9 and 2.8 bar, respectively. Note that inspiratory flow decreased with increasing atmospheric pressures, consequently inspired volume also decreased. Due to these changes, both inspiratory peak and plateau pressures were smaller at high ambient pressures. End-expiratory airway pressure was about 1–2 mbar between 1 and 1.6 bar ambient pressure but decreased to zero at 1.9 and 2.8 bar. Probably the difference is also an effect of the increased density caused by the higher ambient pressure since the valve which regulates the end-expiratory pressure is controlled pneumatically by the ventilator EVITA and this mechanism is likely to be affected by density changes of the driving gas

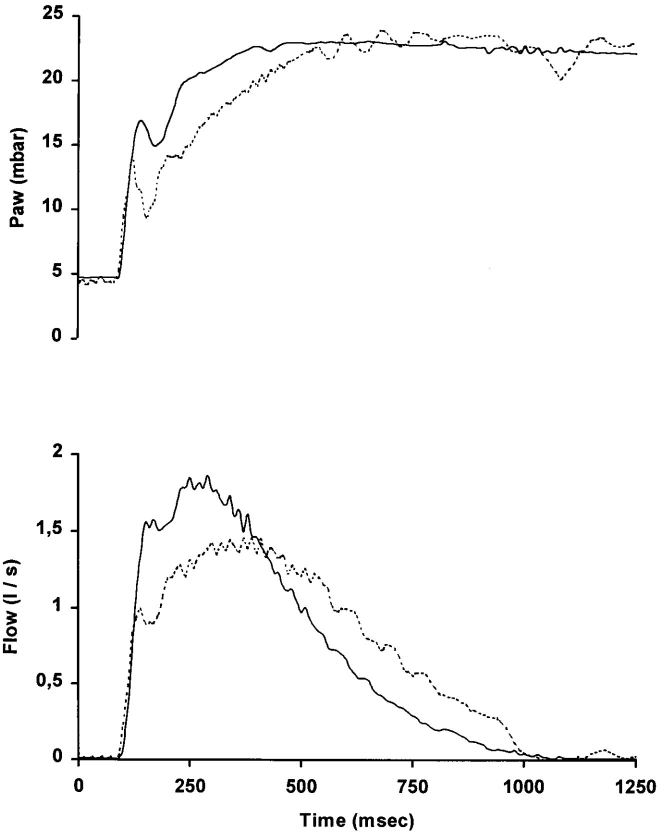


Fig. 3 The diagrams show the typical inspiratory time course of airway pressure (*upper diagram*) and flow (*lower diagram*) at normobaric conditions (*closed lines*) and at 2.8 bar ambient pressure (*dotted lines*) during PCV with the EVITA 4 ventilator. Although both pressure and flow signals are initially almost identical regardless of the ambient pressure, their increment is stopped and downregulated at lower values during hyperbaric exposure. As further explained in the text, this phenomenon is predominantly caused by the decreased maximum volume flow delivery of the ventilator at increased ambient pressure. Further note that cutting off inspiration before flow has reached zero will cause the inspired volume to decrease to a larger extent with increased ambient pressure when compared to normobaric conditions

for each type of ventilator. (2) During PCV respirator functioning is only slightly affected at hyperbaric conditions, V_T being almost stable at each environment pressure despite a moderately slower flow delivery at high pressures. (3) The V_T values displayed by the ventilators generally overestimate the actual ones, probably misleading the inexperienced user.

Volume-controlled ventilation at high ambient pressure

The decrease in inspiratory flow and V_T observed during VCV are clearly the result of the increased gas density at high ambient pressures. During VCV inspiratory flow is

Table 1 Ventilator function during volume controlled ventilation at different ambient pressures

Ambient Pressure	EVITA 4	Flow = 666 ml/s, f = 10/min			Flow = 833 ml/s, f = 15/min				Flow = 1000 ml/s, f = 20/min			
	V_T	$V_{T\,display}$	P_{peak}	$P_{plateau}$	V_T	$V_{T\,display}$	P_{peak}	$P_{plateau}$	V_T	$V_{T\,display}$	P_{peak}	$P_{plateau}$
1	790	761	22 (22)	17 (17)	790	774	23 (23)	18 (18)	790	777	24 (23)	18 (17)
1.3	660	777	18 (19)	15 (14)	650	772	19 (19)	15 (15)	650	776	20 (20)	15 (14)
1.6	540	786	16 (16)	13 (12)	530	787	16 (16)	13 (12)	540	790	17 (17)	12 (12)
1.9	450	820	13 (13)	10 (9)	450	813	13 (13)	10 (9)	450	813	14 (14)	9 (9)
2.8	350		10 (10)	10 (9)	370		11 (11)	9 (8)	350		11 (11)	9 (9)
	Servo 900C	Flow = 515 ml/s, f = 10/min			Flow = 770 ml/s, f = 15/min				Flow = 1000 ml/s, f = 20/min			
	V_T	$V_{T\,display}$	P_{peak}	$P_{plateau}$	V_T	$V_{T\,display}$	P_{peak}	$P_{plateau}$	V_T	$V_{T\,display}$	P_{peak}	$P_{plateau}$
1	772	738	22 (18)	18 (17)	773	733	25 (21)	18 (17)	751	722	26 (22)	18 (17)
1.3	678	702	19 (18)	17 (15)	676	700	21 (18)	17 (15)	686	697	22 (20)	17 (16)
1.6	626	690	19 (18)	15 (14)	626	682	20 (18)	15 (14)	628	666	21 (19)	16 (15)
1.9	571	658	18 (16)	15 (13)	574	662	18 (16)	15 (13)	587	655	21 (18)	16 (15)
2.8	495	637	16 (14)	13 (12)	495	630	18 (16)	14 (13)	499	606	19 (17)	14 (12)
6	395	559	13 (11)	11 (10)	372	536	14 (13)	11 (10)	364	521	15 (12)	11 (10)
	Microvent	Flow = 325 ml/s, f = 10/min			Flow = 564 ml/s, f = 15/min				Flow = 750 ml/s, f = 20/min			
	V_T	$V_{T\,display}$	P_{peak}	$P_{plateau}$	V_T	$V_{T\,display}$	P_{peak}	$P_{plateau}$	V_T	$V_{T\,display}$	P_{peak}	$P_{plateau}$
1	760	680	23 (19)	Not available	750	720	22 (21)	Not available	850	800	25 (25)	Not available
1.3	660	650	19 (17)		620	707	20 (19)		720	770	22 (23)	
1.6	580	630	17 (16)		550	646	18 (18)		640	750	20 (19)	
1.9	530	630	16 (16)		480	640	16 (16)		580	735	18 (19)	
2.8	440	650	13 (14)		400	646	14 (14)		450	720	15 (15)	
6	329	650	10 (9)		285	700	11 (11)		297	680	12 (11)	
	Oxylog 2000 HBO	Flow = 460 ml/s, f = 10/min			Flow = 680 ml/s, f = 15/min				Flow = 890 ml/s, f = 20/min			
	V_T	$V_{T\,display}$	P_{peak}	$P_{plateau}$	V_T	$V_{T\,display}$	P_{peak}	$P_{plateau}$	V_T	$V_{T\,display}$	P_{peak}	$P_{plateau}$
1	919	750	25 (22)	Not available	906	750	26 (22)	Not available	887	760	29 (24)	Not available
1.3	743	730	24 (19)		763	750	26 (20)		746	740	28 (21)	
1.6	653	740	21 (17)		670	750	24 (17)		656	750	25 (19)	
1.9	590	740	19 (16)		604	830	21 (17)		590	750	24 (17)	
2.8	475	730	17 (12)		480	700	20 (14)		471	750	26 (14)	

Abbreviations are: V_T = tidal volume, $V_{T\,display}$ = V_T-values obtained from the ventilator's display, P_{peak} = maximum inspiratory airway pressure and $P_{plateau}$ = end-inspiratory airway pressure (P_{peak} and $P_{plateau}$-values not in parenthesis were obtained from the ventilator's display and those in parenthesis have been obtained from the pressure signal measured inside the bellows). $P_{plateau}$-values are not displayed by the Microvent and the Oxylog 2000 HBO ventilators. The $V_{T\,display}$-values of the Microvent and Oxylog 2000 HBO ventilators were obtained by dividing the minute ventilation given on the display by the respiratory rate. $V_{T\,display}$-values registered at 2.8 bar with the ventilator EVITA was not reliable and therefore not considered here. Probably, it was overestimated under these conditions due to a slight leakage of the inspiratory valve.

kept constant throughout inspiration, and its value is internally adjusted by the ventilator to meet the actual user settings by adjusting the opening of the inspiratory valve. However, the relationship between inspiratory valve opening and volume flow is constant only for each specified inspiratory gas density. Hence, increasing gas density by compression will cause the volume flow to decrease when the degree of valve opening is kept constant. The negative relationship between ambient pressure and V_T further confirms the validity of these theoretical concepts. Intriguingly, however, this relationship between V_T and ambient pressure is anything but equal one, and specific for each ventilator tested. These differences indicate the role of the specific designs of the inspiratory valves and flow-controlling mechanisms of each machine. In spite of the validity of the theoretical concepts just described, therefore, an exact theoretical prediction of ventilator functioning with increased ambient pressure is not possible without precise knowledge and consideration of such details of their technical design. By contrast, a simpler but equally precise prediction of their functioning with increased ambi-

Table 2 Ventilator function values during pressure controlled ventilation

Ambient pressure (atm)	EVITA 4		
	V_T (ml)	V_{max} (l/s)	V_{delay} (msec)
1	770	1.91	161
1.3	780	1.71	193
1.6	770	1.64	213
1.9	770	1.55	222
2.8	810	1.47	270
Ambient pressure (atm)	Servo 900C		
	V_T (ml)	V_{max} (l/s)	V_{delay} (msec)
1	790	1.62	134
1.3	791	1.46	186
1.6	784	1.36	221
1.9	793	1.33	238
2.8	812	1.21	228
6	857	1.06	293

Abbreviations are: V_T = tidal volume, V_{max} = maximum inspiratory flow, V_{delay} = time delay from onset of to maximum inspiratory flow.

ent pressure can be achieved based on empirical data as just presented.

Our observations are absolutely in line with previous studies on respirator functioning with VCV mode performed on different models [2, 3]. Despite these qualitatively similar observations, however, it should be emphasized that each specific model behaves differently in terms of absolute error under hyperbaric conditions. This model-specific relationship between inspiratory valve opening and applied flow must be known if the altered ventilator functioning has to be compensated for.

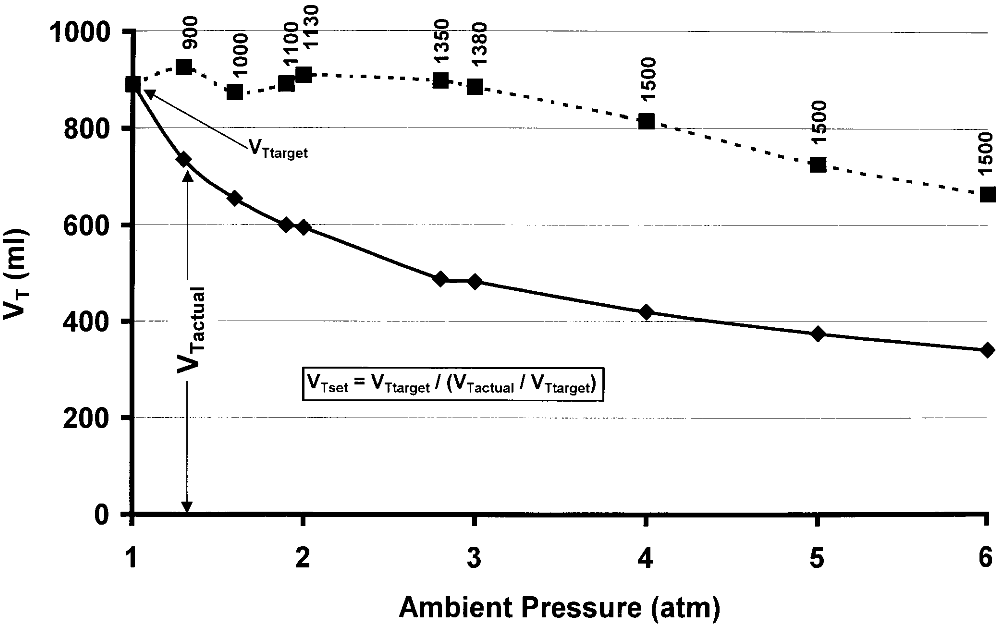
Pressure-controlled ventilation

On PCV, V_T remains stable at each ambient pressure and, therefore, this mode should be preferentially used whenever available. However, one should keep in mind that, even during PCV, inspiratory flow becomes slightly slower at high ambient pressures. Similar to the effects observed during VCV, this phenomenon might derive from the increased resistance to gas flow across inspiratory valves at high ambient pressures. Although, during PCV, the pressure control algorithms will largely compensate this effect by adapting the degree of inspiratory valve opening in order to achieve the pressure level set by the user, the maximum volume flow delivery of each ventilator decreases constantly with hyperbaric conditions, thus limiting the range of this compensation. This mechanism predominantly determined the effects on V_{max} and V_{delay} observed during PCV under hyperbaric conditions. In addition, gas inertia as well as the increased resistance of the ventilator's tubing system at high ambient pressure will slightly affect both flow-related variables, but presumably only to a minor degree.

Despite the observed changes in flow delivery, V_T remains stable at each ambient pressure since the slower initial flow is sufficiently compensated by a higher flow in the later phase of inspiration (see Fig. 3).

It should be noted that our measurements were performed at "normal" airway resistance. This implies that the inspiratory time was sufficiently long at each ambient pressure to permit complete inspiration, as is suggested by the presence of end-inspiratory zero-flow conditions. In situations where the flow does not reach the zero level at end inspiration, however, e.g. in patients with in-

Fig. 4 Correcting the preset tidal volume (V_{Tset}) based on the formula reported in the graph allowed for compensation of the decrease at high ambient pressure (*closed line and rhomboids*). The calculated V_{Tset} values are reported beneath the *closed squares*, which indicate the actual values of V_T achieved after correction (*dotted line*). Note that at high pressures the V_T decrease can no longer be compensated for since the V_T setting range up to 1500 ml/breath is lower than necessary



creased airway resistance, increased ambient pressure will cut off inspiration at a point in time where the flow is still higher when compared to normobaric conditions. Since the volume inspired up to this point will consequently decrease as a function of the ambient pressure, V_T might decrease under hyperbaric conditions even during PCV. For that reason, the use of PCV has been discouraged in the past [7]. If a closed observation of the flow curve is guaranteed, however, harmful decreases in V_T can be easily recognized and, if necessary, compensated for by adjusting the inspiration time, i. e. I:E ratio.

Monitoring respirator functioning and ventilation under hyperbaric conditions

One of the most intriguing results of our investigation is that flow monitoring of each ventilator becomes consistently inaccurate with increasing ambient pressure, thus potentially misleading the user. In fact expiratory flow, and consequently V_T values displayed by the ventilators, were generally higher than in reality, and they have to be corrected appropriately for safe use of the ventilator. In contrast, airway pressures are reliably measured regardless of the ambient pressure and might therefore be useful to estimate the true V_T under such conditions. However, one should be aware of the fact that, with increased ambient pressure, airway resistance will also increase. When keeping inspiratory flow and V_T constant, therefore, plateau pressure will remain unchanged but peak pressure will rise.

Compensation for altered ventilator functioning

Taking into account the measured effects of increased ambient pressure on volume flow delivery, altered ventilator functioning during VCV can be easily compensated at each barometric pressure. As demonstrated by the data presented in Fig. 4, correcting the preset V_T according to the equation

$$V_{Tset} = V_{Ttarget}/(V_{Tactual}/V_{Ttarget})$$

theoretically yields constant V_T values regardless of the ambient pressure. The limit of this compensation, however, is imposed by the upper V_T range allowed for each specific ventilator model and was reached for the ventilators studied between 2 and 3 bar. It is self-evident that the limit of V_T compensation will depend on the actual V_T and will therefore be met at lower ambient pressures the higher V_T actually is. If V_T decreases during PCV, caused by the mechanisms mentioned above, it can be adequately restored by increasing the inspiratory time up to the point where flow reaches zero before the onset of expiration. Additionally, the inspiratory pressure rise time should be adjusted to compensate for the slower initial flow delivery.

In summary, our results show how the functioning of currently available ICU ventilators is altered if they are used under hyperbaric conditions. The most important message of our data is that, if the specific effects of hyperbaric exposure on ventilator functioning are known, ventilator settings can and should be adapted to maintain constant ventilation over a wide range of ambient pressure. Otherwise, without appropriate corrections ventilatory support might become inadequate during hyperbaric exposure.

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