

Title: Volume-controlled ventilation with Breas LTV 1000 ventilators under hypobaric conditions. A lung simulator analysis.

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Abstract: The successful functioning of ventilators under varying ambient conditions depends strongly on barometric pressure and gas density. We examined volume-controlled ventilation using the LTV 1000 Breas ventilator under hypobaric conditions in a typical high altitude profile. The LTV 1000 ventilator administers significantly higher tidal volumes at altitudes above 5000 feet ($P_{\text{BARO}}=633$ mmHg), surpassing the reference ranges ($V_T \pm 10\%$) of all selected tidal volumes. The mean volume increase was 235 ± 66 mL for $V_T=500$ mL, 296 ± 83 mL for $V_T=700$ mL and 414 ± 77 mL for $V_T=1000$ mL. The reason for this lies in the physical changes defined by Boyle's Law, which lead to volume expansion at low pressure and faulty flow measurements of expiratory volumes due to changes in gas density. Appropriate monitoring is thus recommended when using the LTV 1000 ventilator in volume-controlled ventilation mode under varying ambient conditions above 5000 feet. The analysis produces a reference value for the reduction in the ground normal tidal volume of 3% per 1000 feet.

Introduction

Intubation and mechanical ventilation are indicated in about 10 to 15% of German air rescue cases. In only 46.2% of cases investigated in Germany is sufficient ventilation administered during preclinical ventilation therapy, irrespective of the rescue assets used [6]. The reasons for this are believed to be the lack of monitoring and the ventilation technique applied [5]. Little has been done, however, to analyse the role of ventilators under hypobaric conditions, i.e. in an air rescue situation [2]. The medical technology employed during air rescue operations is subject to physical laws that can influence the treatment of the patients transported. Tidal volume, respiratory gas flow and the administration of oxygen are important for ventilation under hypobaric conditions, since respiratory gases, unlike liquids, are compressible and their volumes thus change along with the barometric pressure. This general rule is reflected in Boyle's Law ($P_1 \times V_1 = P_2 \times V_2$). The changes in barometric pressure (P_{BARO}) are specified in the barometric formula $[p(h) = p_0 \times e^{-(g_0 \times g / p_0) \times h}]$ and depend on the altitude. Investigations showed that the emergency respirators of Breas (Oxylog 1000 and 2000), which were not conceived especially for the air rescue service, were useless for intensive artificial respiration [2]. The LTV 1000 intensive ventilator by Breas Medical® is frequently used during German interhospital transfer via helicopter (BK 117 and Bell 412) and in the armed medical forces during medical evacuation operations (MedEvac) via aeroplanes such as the Airbus A 310 and Transall C160. In the four German MedEvac A 310 aeroplanes alone, 24 LTV 1000 ventilators are used.

The LTV 1000 ventilator is a microprocessor-controlled ventilator that can be used under ambient conditions of 10°C to 40°C and 700 hPa to 1060 hPa (526 mmHg to 796 mmHg) [2]. The tolerance for inspiratory and expiratory volumes is $\pm 10\%$. A deviation of $\pm 8\%$ is allowed between the flow settings and the flow measured for the tidal volume and respiratory minute volume measurements. The desired gas mixture is achieved by means of high-pressure servo valves (HPSV). Generally, the pressure set up in the ventilator is defined as division by volume and compliance and multiplication

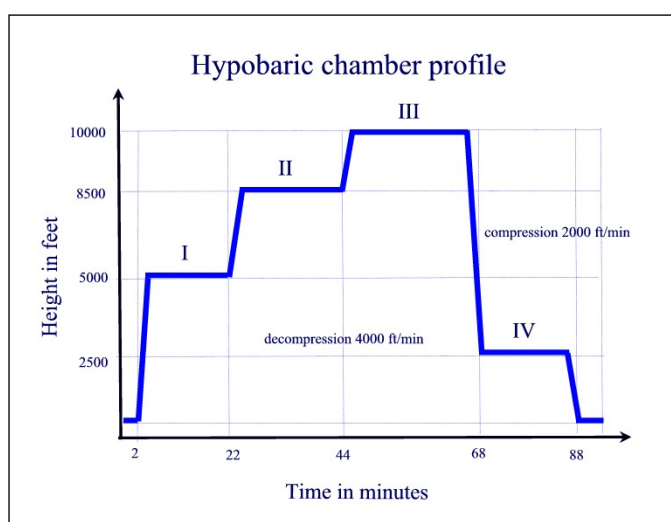
by flow and resistance. The evaluation of the respiratory gas flow plays a special role during the analysis, since the compliance and resistance of the lung simulator in use remain constant under varying ambient conditions and, thus, a definite conclusion can be drawn about the inspiratory volume.

This paper will examine the functional efficiency of the LTV 1000 ventilator under varying ambient conditions using a lung simulator independent of barometric pressure in a hypobaric chamber.

Material and methods

The measurement was set up in the hypobaric chamber of the Air Force Institute of Aviation Medicine, Department of Flight Physiology, in Königsbrück. Functional verification of the ventilator occurred in the hypobaric chamber at ground level (740 mmHg). The ventilator (LTV 1000, Breas Medical AG & Co. KGaA, Lübeck) was attached to an oxygen cylinder filled to 200 bar (Air Products Hattingen 3.0 L; TGL 100) with a 4.5 bar pressure regulator (Oxyway pressure regulator, Weinmann Hamburg, Type: Fix WM 30301; $P_1=200$ bar; $P_2=4.5$ bar; $Q_1=120$ L/min). The device was also connected to a compressed air cylinder (UN No. 1002; 3.0 L) with a 4.5 bar pressure regulator (Breas, Type: WRLD-7084). The temperature of the gases was $21 \pm 0.5^\circ\text{C}$ during the analysis. The tidal volumes (V_T) were set to 500, 600, 700 and 1000 mL using the displays. The inspiratory/expiratory time ($T_{\text{insp}}/T_{\text{exp}}$) setting was 1:2, which corresponded to a T_{insp} of 2 s with a respiratory rate of 10 min^{-1} . Positive end expiratory pressure (PEEP) was not applied (PEEP = 0 mbar). In the intermittent positive pressure ventilation (IPPV) mode, pressure limitation was not activated ($p_{\text{max}} = 120$ mbar). The F_{O_2} of all reference measurements was 0.50. The ventilator was attached to an Active Servo Lung (ASL) 5000 computer-based lung simulator (ASL 5000; IngMar Medical, Pittsburgh, USA) using pressure-resistant ventilation tubes designed specifically for the device. The simulator was controlled externally from a computer. The defined compliance was 50 mL/cm H_2O , while the resistance was set at 5 cm $\text{H}_2\text{O}/\text{L/s}$ in a simulated one-compartment model. Measurements were carried out for 20 min at I=5000 feet (633 mmHg), II=8500 feet (554 mmHg), III=10,000 feet (524 mmHg) and also IV=2500 feet (695 mmHg). The change in the decompression was 4000 feet/min and the change in the compression was 2000 feet/min. The temperature and relative humidity were held constant at 20°C and 50%, respectively. The resulting hypobaric chamber profile is shown in Figure 1.

Figure 1: Altitude-time diagram of the hypobaric chamber experiment.



For metrically scaled and normal distributed data we used the test for dependent groups. For statistical evaluation purposes, a student t -test was conducted and the level of significance was always set at $p<0.05$.

Results

During volume-controlled ventilation, the readings on the LTV 1000 (LTV) of the indicated tidal volume¹ and the volumes measured by the Active Servo Lung (ASL)³ differed significantly for all measurements. The tidal volumes listed in Table 1 are expiratory values.

When the selected tidal volume was 500 mL, the mean difference between the volume measurements (ASL vs. LTV) at all simulated altitudes was 235 ± 34 mL / breath. At a tidal volume of 600 mL, the difference measured amounted to 250 ± 66 mL / breath. The divergence for a tidal volume of 700 mL averaged 296 ± 83 mL / breath. When 1000 mL was selected, the volume difference increased to an average 414 ± 77 mL / breath.

At a tidal volume of 500 mL, the difference between the selected tidal volume² and the measured volume³ amounted to 65 mL / breath; at 600 mL the difference was 96 mL / breath; at 700 mL, the volume difference increased to an average 115 mL / breath; and when 1000 mL was selected, an average volume increase of 174 mL / breath was measured. In the course of the measurements, a decrease in the indicated tidal volumes¹ of the LTV 1000 occurred, depending on the altitude, while an increase in the volumes measured³ by the ASL was noted. The values shown in Table 1 are average values calculated from 10 individual measurements of the respective volumes. If we take into account the device-specific reference range of the tidal volume, significant changes of 14–26% occurred at all volume levels at a barometric altitude of 8500 feet. At 10,000 feet, the divergences increased to up to 30–34%.

Table 1: LTV 1000 vs. Active Servo Lung (ASL) 5000 tidal volume measurements (mean $\pm$ SD) during volume-controlled ventilation.

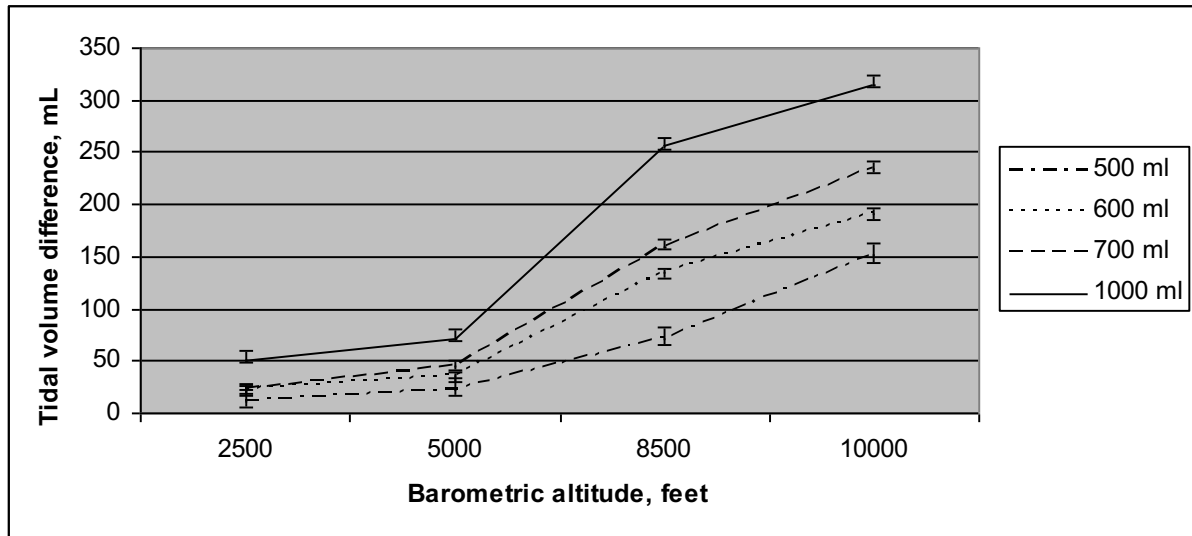
Barometric altitude in feet	2500	5000	8500	10,000
Barometric pressure in mmHg	695	633	554	524
Barometric pressure in psi	13,44	12,24	10,71	10,13
²Selected tidal volume in mL	500	500	500	500
¹ Indicated tidal volume E4 in mL	370.7* $\pm$ 11.7	354.7* $\pm$ 2.5	306.7* $\pm$ 19.0	352.7* $\pm$ 4.0
³ Measured volume – ASL in mL	511.9 $\pm$ 1.0	521.1 $\pm$ 1.3	567.3** $\pm$ 18.8	646.7** $\pm$ 2.8
⁴ Peak flow in mL/s	1157.8 $\pm$ 1.7	1196.5 $\pm$ 2.2	1336.6 $\pm$ 39.7	1553.7 $\pm$ 8.4
²Selected tidal volume in mL	600	600	600	600
¹ Indicated tidal volume E4 in mL	425.3* $\pm$ 8.4	424.0* $\pm$ 2.6	409.7* $\pm$ 5.1	417.3* $\pm$ 1.5
³ Measured volume – ASL in mL	621.9 $\pm$ 12.4	630.3 $\pm$ 1.0	733.8** $\pm$ 0.5	785.1** $\pm$ 5.0
⁴ Peak flow in mL/s	1410.8 $\pm$ 27.0	1452.3 $\pm$ 1.6	1718.1 $\pm$ 2.0	1924.9 $\pm$ 64.8
²Selected tidal volume in mL	700	700	700	700
¹ Indicated tidal volume E4 in mL	488.3* $\pm$ 3.2	486.3* $\pm$ 9.5	478.3* $\pm$ 4.2	502.3* $\pm$ 3.2
³ Measured volume – ASL in mL	722.1 $\pm$ 1.1	739.2 $\pm$ 1.8	855.2** $\pm$ 4.0*	929.1** $\pm$ 0.4
⁴ Peak flow in mL/s	1635.8 $\pm$ 4.9	1695.3 $\pm$ 3.1	2015.5 $\pm$ 16.7	2229.6 $\pm$ 0.5
²Selected tidal volume in mL	1000	1000	1000	1000
¹ Indicated tidal volume E4 in mL	709.0 $\pm$ 6.0*	707.3 $\pm$ 15.0*	710.7 $\pm$ 14.7*	687.3 $\pm$ 6.7*
³ Measured volume – ASL in mL	1050.1 $\pm$ 1.2	1067.8 $\pm$ 3.4	1252.1 $\pm$ 4.8*	1314.8 $\pm$ 3.6
⁴ Peak flow in mL/s	2363.4 $\pm$ 2.3	2428.6 $\pm$ 6.0	2920.4 $\pm$ 8.8	3125.8 $\pm$ 8.9

* Result between E4¹ and ASL³, p<0.05

** Result within ASL³ p<0.05

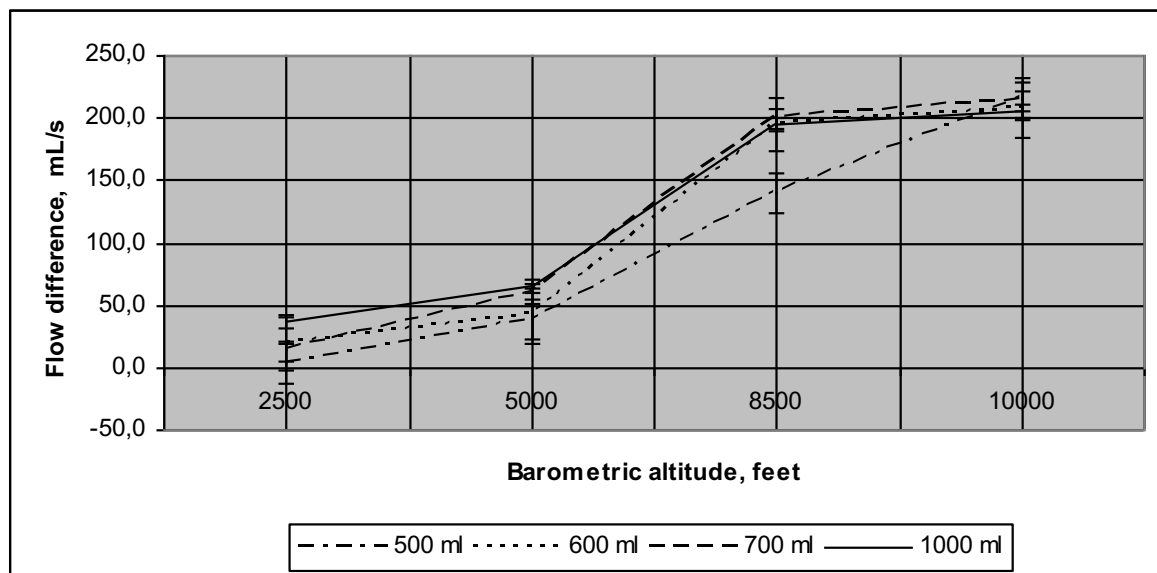
If we consider the differences between the tidal volumes selected in the LTV 1000² and the expiratory volumes measured by the ASL³ lung simulator, increases in the tidal volumes were produced at the respective barometric altitudes as demonstrated in Figure 2.

Figure 2: Differences between the tidal volumes selected in the LTV and measured by the ASL under hypobaric conditions for volume-controlled ventilation (mean $\pm$ SD).



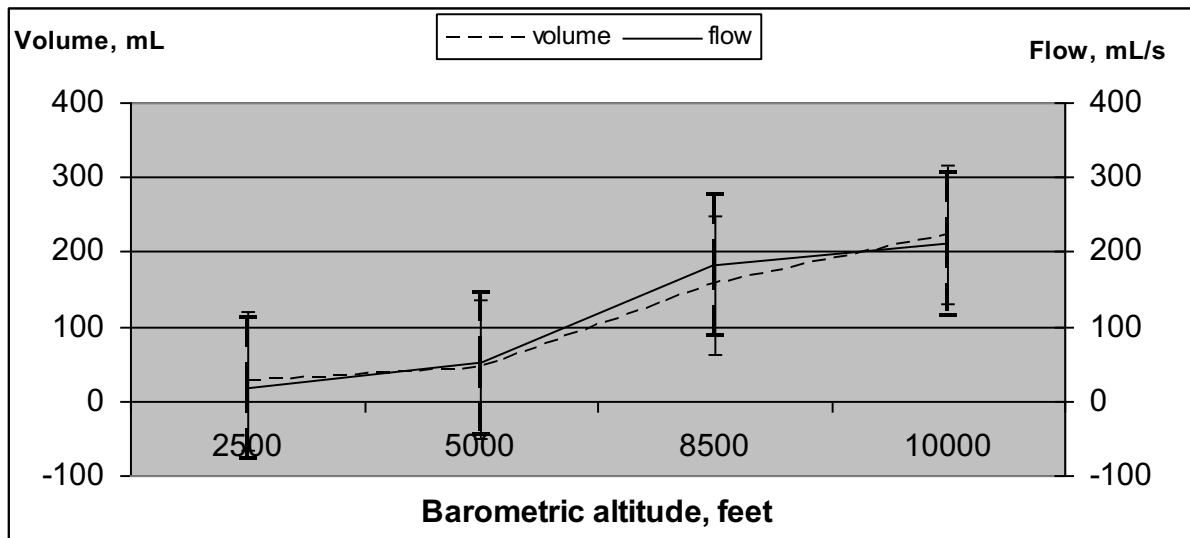
The increase in peak flow during volume-controlled ventilation amounted to an average of 18 mL/s at 2500 feet, 51 mL/s at 5000 feet, 182 mL/s at 8500 feet, and 211 mL/s at 10,000 feet in comparison with peak flow rates measured at ground level (740 mmHg). Airway resistance and lung compliance remained constant. Figure 3 shows the increase in peak flow for volume-controlled ventilation under hypobaric conditions.

Figure 3: Increase in peak flow as a function of altitude during volume-controlled ventilation under hypobaric conditions (mean $\pm$ SD).



The extent to which this increase in flow depends on the volume/mass flow rate is shown in Figure 4. This figure indicates the average volume increases for all tidal volumes administered at the respective levels of the altitude profile, including the corresponding average changes in respiratory gas flow. The correlation between gas flow and volume application is expected to be high ($r = 0.98$), so that in a one compartment model no gas diffusion disorders occur. A comparison of the expiratory tidal volumes measured by the ASL 5000 simulator and the expiratory tidal volumes of the LTV 1000 ventilator produces an inversely proportional correlation ($r = -0.6$).

Figure 4: Volume and flow increases under changing ambient conditions (mean±SD).



The respiratory gas composition of the LTV 1000 ventilator is controlled by high-pressure servo valves (HPSV). The functionality of the HPSV can be tested by exclusively administering air or oxygen. We administered 100% oxygen for tidal volumes of 500 mL and 1000 mL.

Table 2: Volume changes for F_{iO_2} 50% and F_{iO_2} 100

Simulated altitude		Ground, mL	2500 feet, mL	5000 feet, mL	8500 feet, mL	10000 feet, mL
<i>Tidal volumen</i>						
500 ml	F_{iO_2} 50 %	509,3 ml	511,9 ml	524,7 ml	571,9 ml	652,0 ml
	F_{iO_2} 100%	515,6 ml	522,9 ml	526,5 ml	608,1 ml	646,8 ml
1000 ml	F_{iO_2} 50 %	1030,3 ml	1050,7 ml	1071,8 ml	1256,3 ml	1314,8 ml
	F_{iO_2} 100%	1025,7 ml	1025,7 ml	1054,0 ml	1094,2 ml	1311,7 ml

Although for different barometric altitudes changes in volume administration at $V_T = 500$ mL occur with F_{iO_2} 50% in contrast to F_{iO_2} 100%, the statistical result of the t -Test shows no significant divergence, with $p=0.11$. Neither does the volume administered at $V_T = 1000$ mL result in any significant difference between the F_{iO_2} 50% and the F_{iO_2} 100% groups with a statistical t -Test result of $p=0.12$.

Discussion

The hypobaric chamber profile simulates the flying altitudes of helicopters, transport aircraft without sealed cabins, and aircraft with sealed cabins. It thus represents typical ambient conditions encountered in airlifts of patients requiring ventilation. Furthermore, the altitudes of the barometric profile are within the specifications of the LTV 1000 ventilator. No changes in temperature or humidity occurred during the experiments (Figure 1); these conditions also corresponded to the service conditions specified by the manufacturer [4].

During volume-controlled ventilation, a positive pressure is created in the inspiratory phase, distributing the volume produced to the ventilation system according to the barometric pressure and the total compliance in the measurement setting. The total or dynamic compliance is the compliance of the ventilator, tube and the defined compliance of the simulator. Changes in compliance and resistance are of no significance in the simulator for the analysis conducted. Changes in volume can thus be exclusively explained by volume expansions during changes in barometric pressure. Increases in peak flow and volume differ in proportion to the barometric altitude ($r=0.98$). Changes in the

density of the surrounding gas mixture as well as changes in flow resistance lead to faulty readings for the respiratory gas mass flow on the LTV 1000 flowmeter. These changes are inversely proportional ($r=-0.6$) to the expiratory tidal volumes measured by the simulator.

In comparison with the LTV 1000, other respirators deliver similar deviations. The LTV 1000 produced an increase of 252 mL at $V_T=500$ mL and 10,000 feet and an additional increase of 229 mL at $V_T=1000$ mL. The Siemens Servo 300 ventilator delivered an increase of 192 mL at 10,000 feet at $V_T=500$ mL and an additional 435 mL at $V_T=1000$ mL.

Regardless of the gas mixture selected (F_{iO_2} 50% vs. 100%), no significant change in the HPSV function could be detected with a tidal reduction. In preliminary examinations of other ventilators, volume expansion and an increase in the administration of tidal volumes occurred during mechanical ventilation [1]. Additionally, volume expansion of air-filled spaces in patients receiving ventilation under hypobaric conditions makes a further increase in respiratory gas flow likely and, thus, an increase in tidal volume caused by mechanical ventilation.

This analysis proved that the LTV 1000 ventilator produces an increased administration of tidal volumes at higher altitudes. With increasing barometric pressure, this divergence is greater for high tidal volumes than for low volumes. In the strategy of lung protective ventilation to reduce mortality in acute lung injury it is advisable to use lower tidal volumes of 6 mL/kg [1]. However, clinical trials testing low volumes in ALI and ARDS have not shown uniform results [3]. These trials investigated lower tidal volumes (5-7 mL/kg) with $V_T=500$ mL, than traditional tidal volumes (10 mL/kg or more) with $V_T=1000$ mL. Our study showed that intended lower tidal volumes during hypobaric conditions are safer for air medical transport because there is less error than in delivering higher tidal volumes at high altitude.

Another aggravating factor is the varying dynamics of the respiratory parameters. Decreasing, faulty indications of tidal volumes on the LTV 1000 ventilator (indicated tidal volume¹ on E4 in mL) additionally increase the risk of a ventilation-related barotrauma of the lungs. While the tidal volumes administered by LTV 1000, determined by flow sensors, at 2500 feet amount to a decrease of 18 mL for a tidal volume of 500 mL, the volumes for a tidal volume of 1000 mL decrease by 136 mL. In contrast, however, an actual increase in volumes occurs (measured volume³ by ASL in mL, Table 1). If the high-pressure servo valves (HPSV) are piloted separately (F_{iO_2} 50% versus F_{iO_2} 100%), no significant differences occur in the administration of higher gas volumes. It can thus be assumed that the gas sensors are responsible for the divergences in readings under varying ambient conditions.

Conclusions

LTV 1000 is an intensive ventilator whose function is subject to changes in barometric pressure. Measurements of the respiratory volumes indicated by the LTV 1000 ventilator and those measured by the ASL lung simulator differ considerably. Above 5000 feet, all respiratory parameters of volume control are found to be outside the reference range. Here, the extent of the divergence depends on the simulated flying altitude, the magnitude of the tidal volume and the administered respiratory gas flow. Impairment of the functional efficiency of the ventilator caused by the high-pressure servo valves (HPSV) can be ruled out. Consequently, a functional deviation of the flow sensors depending on barometric pressure must be assumed, meaning that an evaluation of end expiratory respiratory parameters is not appropriate for assessing the true functionality of the ventilator. The use of volumeters (e.g. Wright respirometer) would be a reasonable alternative. An exact monitoring system must primarily provide the breath dynamic parameters such as resistance and compliance.

Knowledge of the maximal volume deviation of 30%, for $V_T=1000$ mL at 10,000 feet, yields a quotient for the tidal volume reduction. The analysis produces a reference value for the reduction of the ground normal tidal volume of 3% per 1000 feet. For $V_T=1000$ mL, this corresponds to a conversion factor of 0.70. At an altitude of 10,000 feet the tidal volume must be reduced by 300 mL.

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