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Evaluation of ventilators used during transport of ICU patients – a bench study

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Abstract *Objectives*: To evaluate portable ventilators. *Design and settings*: Bench study. *Materials and methods*: Five portable ventilators used for transporting ICU patients [Osiris 1, (ventilator a), Osiris 2, (ventilator b), Oxylog 1000, (ventilator c), Oxylog 2000, (ventilator d), AXR1a, (ventilator e)] and three ICU ventilators which can be used for this purpose [Horus, (ventilator f), T-Bird, (ventilator g), and SV 300, (ventilator h)] were compared using a test lung regarding: 1) their capability to maintain set tidal volumes (V_T) of 300 ml, 500 ml, and 800 ml under a normal condition A [resistance (R) 5 cmH_2O/l/s and compliance (C) 100 ml/cmH_20] and two abnormal conditions B (R 20–C 30) and C (R 50–C 100); 2) trapped volume (expired V_T relative to inspired V_T at 0.7 s, 1 s, and 1.4 s), an estimate of the expiratory resistance of both circuit and valve; and 3) the triggering system assessed from the measurements of Δt, ΔP for two inspiratory efforts at a PEEP of 0 cmH_20 and 5 cmH_20 in ventilators b, d, f, g, and h. Flow and airway pressure were measured with an independent physiologic recording system. *Results*: 1) V_T. For ventilators a–h, the mean±SD changes of a set V_T of 300 ml were –2.6±0.2%, –9.7±0.2%, 0±0%, –6.1±0.2%, 1.0±0.3%, –2.1±1.7%, 0.3±0%, and –1.3±0.1% ($P<0.001$), respectively, during condition B relative to A. Similar results were obtained for a V_T of 500 ml and 800 ml and during condition C relative to A; 2) Trapped volume. For ventilators a–h, trapped volume averaged 1±1%, 20±0%, 30±0.4%, 20±1%, 1±0%, 19±0%, 15±0%, and 14±0% at 0.7 s ($P<0.001$) and 0.6±0%, 5±0%, 0.5±0%, 0±0%%, 0±0%, 0.6±0%, 0±0%, and 0±0% at 1.4 s (P=NS); and 3) the triggering system of Oxylog 2000 was poor whereas it was of good quality for Horus, T-Bird, SV 300, and Osiris 2. *Conclusions*: The small portable ventilators presently investigated varied between each other and were less accurate than ICU ventilators.

Keywords Bench study · Portable ventilators · Transporting ICU patients

Introduction

Patients receiving mechanical ventilation in the ICU are frequently transported away for radiological evaluation or surgical purposes [1]. In these patients, mechanical ventilation is applied to either normal or diseased lungs with various degrees of respiratory mechanics impairment, that is, with various combinations and extent of increased resistance and decreased compliance. Therefore, the ventilators used to transport these patients must be reliable enough to efficiently manage these different respiratory conditions, in order to maintain adequate oxygenation and ventilation [2, 3, 4]. The ventilators used for this purpose may be either ICU ventilators or less sophisticated machines [1]. To our knowledge, only a few comparative studies regarding portable ventilators have been published [5, 6, 7]. Hence, with the aim of evaluating the extent to which portable ventilators were able to manage the range of respiratory mechanics derangements, we evaluated – in a bench study – five portable ventilators in comparison to three ICU devices investigated with the same protocol.

Material and methods

Ventilators tested

We tested five portable ventilators (*Osiris 1* and *Osiris 2*, Taema, France; *Oxylog 1000* and *Oxylog 2000*, Drägerwerk, Germany; *AXR1a*, Bio MS, France) and three ICU machines (*Horus*, Taema, France; *T-Bird*, Bird, USA; *SV 300*, Siemens, Germany) that can be used for transport purposes as they have both internal and external batteries. These eight ventilators are commonly used in Europe. The machines were provided by the manufacturers after a full revision had been made just before our investigation. The characteristics of the eight ventilators are shown in Table 1.

Experimental set-up

The experimental set-up (Figs. 1 and 2) comprised of the following parts: 1) a double-chamber test lung (TTL 1600, Michigan Instruments, Grand Rapids, USA); 2) a Fleish 2 pneumotachograph attached to a differential pressure transducer (Validyne; ± 5 cmH_20) for measurement of airflow ($\dot{V}$); 3) a side-port connected to a pressure transducer (Validyne; ±175 cmH_20) for pressure (P) measurement; and 4) the ventilator to be tested. The pneumotachograph was linear over the range of $\dot{V}$ used. The P transducer has no appreciable shift or alteration in pressure amplitude up to

Table 1 Characteristics of the eight ventilators tested

	Osiris 1	Osiris 2	Oxylog1000	Oxylog 2000	AXR1a	Horus	T-Bird	SV 300
Weight (kg)	4.4	5	3.8	4.3	3.7	14	15	25
V_T (ml)		100–1,500		100–1,500		20–1,500	50–2,000	2–4,000
Minute ventilation (l/min)	4–30		3–20	4–60	4–21			
Rate (breaths/min)	10–40	6–40	5–40	5–40	10–40	4–80	2–80	5–150
Positive end-expiratory pressure device	Mushroom	Mushroom	Ambu (external)	Membrane	Ambu (external)	Membrane	Electro-magnetic	Scissor
Peak inspiratory pressure limit (cmH_2O)	100	80	80	60	100	90	120	100
Trigger sensitivity								
(cmH_2O)	Not available	–4 to –1	Not available		Not available	–0.5 to –5		0 to –17
(l/min)				4		0.5–5	1–8	2
Maximal inspiratory flow (l/min)	100	100	NA	100	NA	>200	140	180
Venturi flow-generating device	Yes	Yes	Yes	Yes	Yes	No	No	No
F_iO_2 (%)	60 or 100	60 or 100	60 or 80	60 or 100	50 or 100	21–100	21–100	21–100
Batteries								
Internal	Alarm only	Yes	No	Yes	Alarm only	Yes	Yes	Yes
External	No	No	No	No	No	Yes	Yes	Yes
Expected hours of internal battery life		10		6		1	2	0.5
Circuit compliance (ml/cmH_2O)	0.29	0.29	0.37	0.37	0.43	0.12	0.97	1.26
Circuit								
Length (cm)	90	130	150	150	120	150×2	120×2	150×2
Internal diameter (mm)	19	19	22	22	19	19	19	19

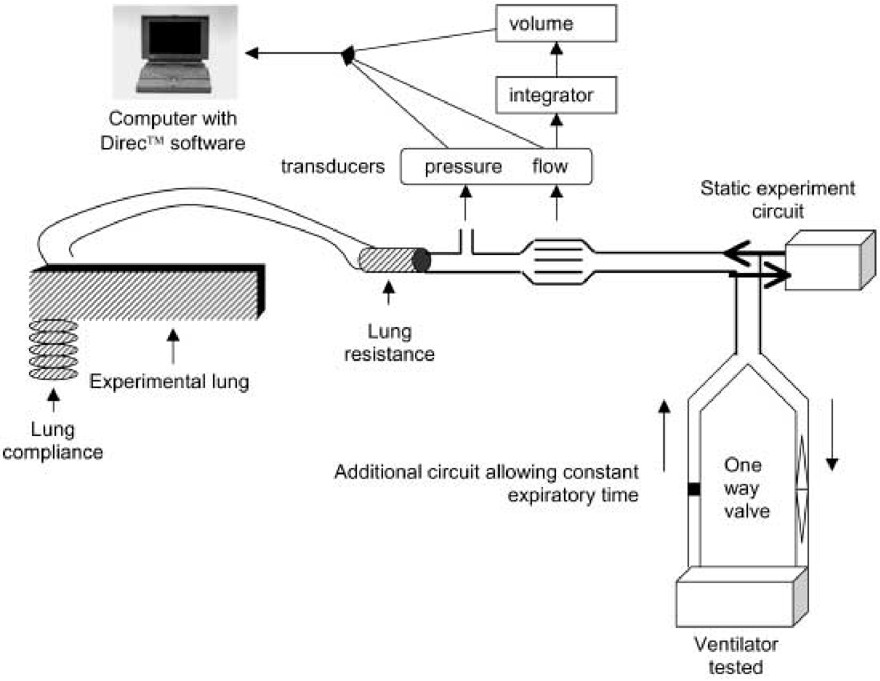


Fig. 1 Scheme of the experimental set-up used for static experiments (*double horizontal large open arrows*) and to test the accuracy of tidal volume delivery. See text for further details

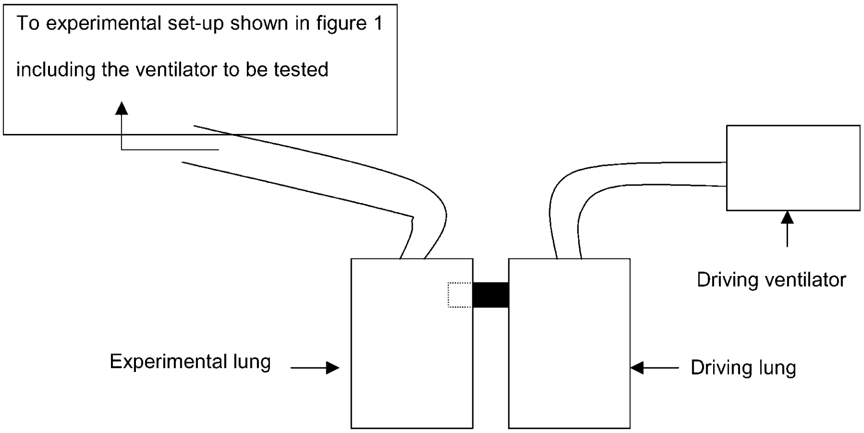


Fig. 2 Scheme of the experimental set-up used for dynamic experiments. See text for further details

20 Hz. Before each experiment, the $\dot{V}$ transducer was calibrated with a 3-l syringe and the P transducer with a water column manometer. During the experiments, the signals of $\dot{V}$ and P were amplified, sampled at 200 Hz using a computer acquisition system with a 16-bit analogic converter and software (Direc recording system, Raytech Instruments, Vancouver, Canada). The data were stored on the computer for subsequent analysis with Anadat software (RHT-Infodat, Montreal, Canada). Volume was obtained from numerical integration of the $\dot{V}$ signal.

Protocols

The test lung was used in two different ways.

Static experiments

In these experiments, both the measurement set-up and ventilator tested were connected to a single lung (Fig. 1). By the variation of lung resistance (R) and/or compliance (C), we defined three different mechanical loads imposed on the ventilators. These were labelled condition A (R 5 $cmH_2O/l/s$ and C 100 ml/cmH_2O) featuring normal ventilatory mechanics, condition B (R 20 $cmH_2O/l/s$, and C 30 ml/cmH_2O) mimicking the acute respiratory distress syndrome, and condition C (R 50 $cmH_2O/l/s$ and C 100 ml/cmH_2O) which may occur in case of acute obstruction of the airways or endotracheal tube or acute severe asthma. We designed experiments to assess how accurately the ventilators delivered tidal volume (V_T) facing these mechanical conditions. In addition, we determined the trapped volume due to the circuit and expiratory valve. All ventilators were operated according to the manufacturer's instructions.

Tidal volume delivery

In this experiment, the experimental set-up shown in Fig. 1 was modified by incorporating a specific circuit in order to obtain a constant duration of the expiratory phase (T_E) during the changes of the resistance of the test lung. The tested ventilator was used in volume controlled mode (VC) with a squared inflation flow, a respiratory rate (f) of 20 cycles/min, and the duration of the inspiratory phase (T_I) being 1 s. Nominal values of V_T of 300 ml, 500 ml, and 800 ml were set for each ventilator for each mechanical condition. The measurements were carried out on three to five consecutive breaths. The measurements actually delivered by the ventilator and the set values of V_T were compared. We also compared the relative changes of tidal expired V_T (V_TE) between conditions B and C and condition A taken as the normal reference.

Trapped volume

We used the records obtained from the above experiments carried out at a V_T of 500 ml with an R of 5 $cmH_2O \cdot l \cdot s$. We measured V_T at 1.4 s, 1 s, and 0.7 s from the onset of expiration. These time delays would correspond to an f of 25 cycles/min, 30 cycles/min, and 35 cycles/min, respectively. Then, we computed the ratio of these partial V_TE to the V_T of the preceding inflation. We reasoned that should this ratio reflect the volume of gas trapped, the greater this ratio the greater the resistance offered to the airflow by the circuit and the expiratory valve of the ventilator.

Dynamic experiments

These experiments were done to assess the *triggering sensitivity* of the inspiratory valves of the Osiris 2, Oxylog 2000, Horus, T-Bird, and SV 300 ventilators. The experimental set-up was used as shown in Fig. 2. One lung (driving lung) was powered by a Cesar ventilator (Taema, France) set in VC mode, squared inflation flow, f 12 cycles/min, and T_I 30% of the total respiratory cycle duration. The experimental lung was attached to the ventilator under evaluation. Compliance values of 30 ml/cmH_2O and of 80 ml/cmH_2O were adjusted to the driving and experimental lungs, respectively, whereas resistance was set-up for each lung with a size 8 endotracheal tube. The two lungs were connected with a small metal insert. The establishment of a positive pressure in the driving lung created a sub-atmospheric pressure in the experimental lung that triggered the ventilator to be tested. As the time constants of the two lungs were different it was necessary to apply PEEP to the driving lung to avoid separation between compartments at end-expiration. The triggering systems of the different ventilators were set at their maximal sensitivities. Osiris 2, T-Bird, and Oxylog 2000 were flow triggered. SV 300, which is either flow or pressure triggered, was used in its flow-triggering configuration. Horus is flow triggered at PEEP 0 and pressure triggered at PEEP >0. To mimic normal and strong inspiratory efforts by patients, the V_T of the driving ventilator was set at 220 ml and 440 ml, respectively. These efforts were actually associated with a pressure 100 ms after occlusion ($P_{0.1}$) of 2 cmH_2O and 4 cmH_2O, respectively, as measured on the bench. The measurements were done at a PEEP of 0 cmH_2O and 5 cmH_2O for each of the two different efforts. To assess the performance of the triggering systems of the ventilators, we measured both the reduction in pressure (ΔP, cmH_20) and the time delay (Δt, ms) required to open the inspiratory valve (Fig. 3). We therefore computed the pressure-time product (PTP, $cmH_20 \times ms$) as $\Delta P \times \Delta t$.

The compliance of the circuit of all the ventilators was measured before each experiment. The measurements were made at F_iO_2 of 60% in all ventilators, with the Venturi system at work in those ventilators equipped with it.

Statistical analysis

Continuous variables were expressed as mean±SD values obtained from three to five consecutive breaths. These variables were compared using a two-way repeated measures ANOVA. Given the large number of comparisons performed during this study, Bonferroni's correction was applied and the level of significance of type I errors set at less than 0.001. When the global F was significant, a multiple comparison was done using Tukey's or Dunnett's test. The α-level of Tukey's and Dunnett's tests was also set at less than 0.001. For our statistical analysis, we used SigmaStat software for Windows version 2.03 (SPSS, Chicago, Ill., USA).

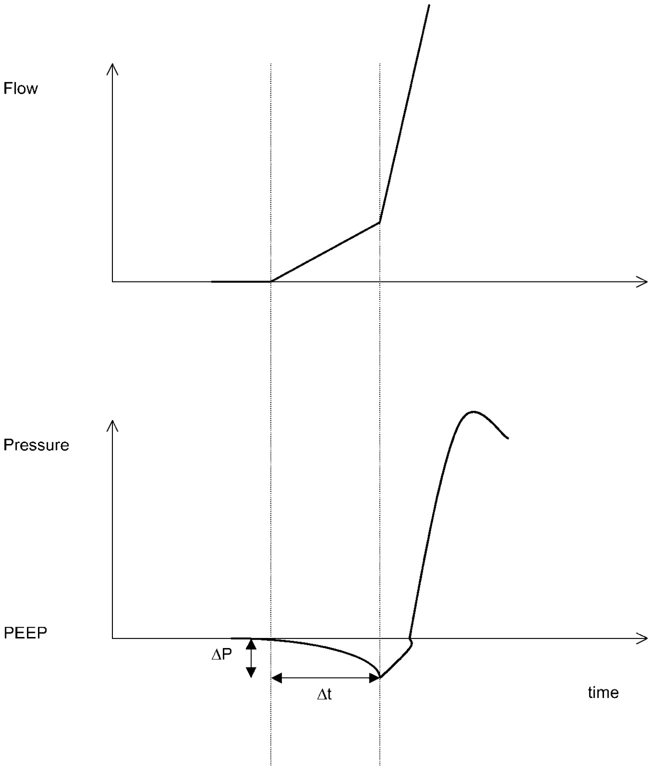


Fig. 3 Schematic drawing of the assessment of the performance of the ventilator triggering systems. ΔP and Δt are the changes in pressure and time delay, respectively, required to open the inspiratory valve. The triggering systems were adjusted to their maximal sensitivity

Results

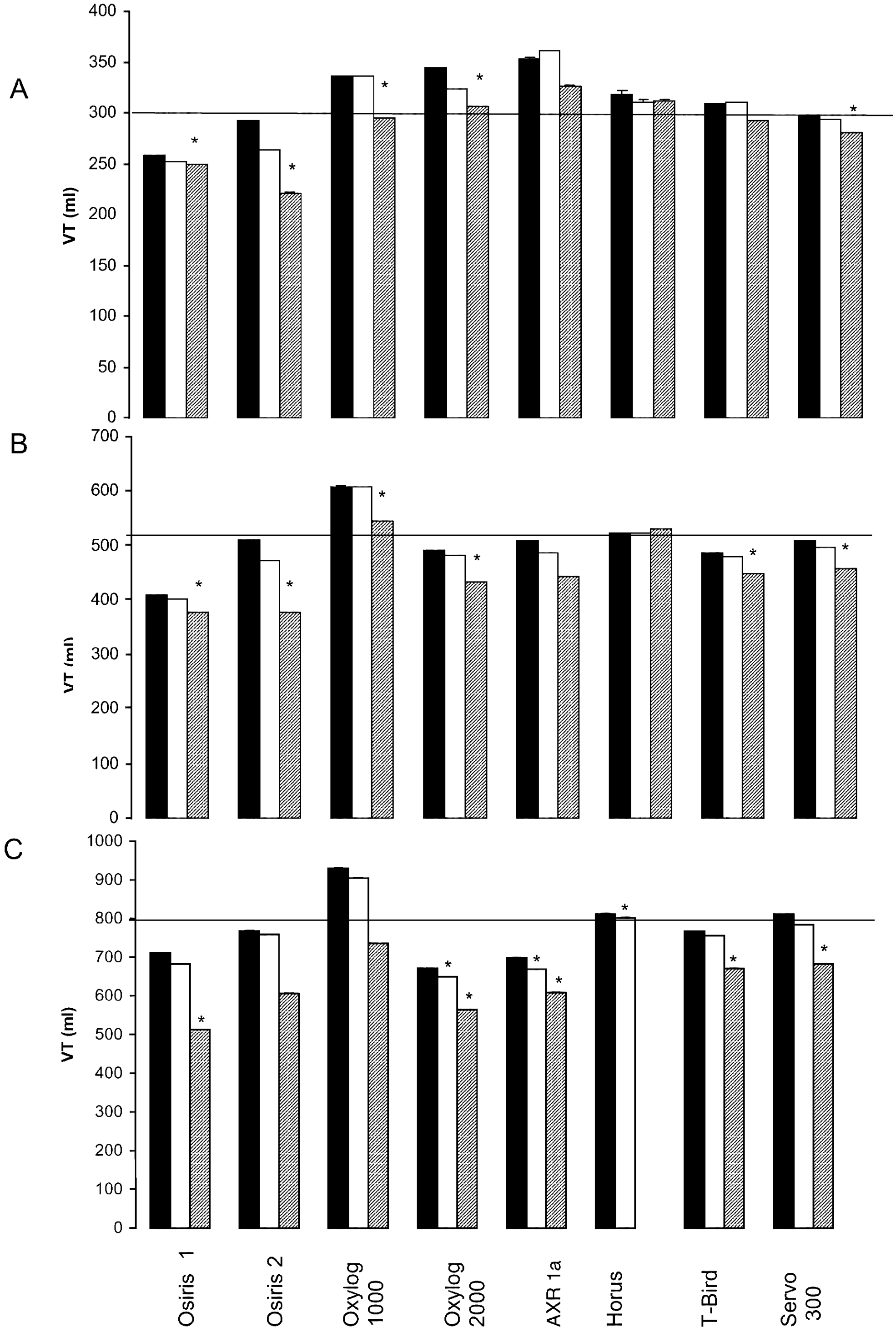
Tidal volume delivery

The values of V_T delivered by the ventilators during the three mechanical conditions for the three selected V_T are shown in Fig. 4. It must be noted that a V_T of 800 ml could not be delivered for Horus in condition C due to the upper safety limit of airway pressure being no greater than 90 cmH_2O.

Control condition

Under control condition A (Fig. 4), Osiris 1 delivered less V_T whereas Oxylog 1000 delivered more V_T

Fig. 4A–C Mean values of tidal volumes (V_T) delivered from the ventilators during three mechanical conditions: A (*black rectangles*), B (*white rectangles*), and C (*hatched rectangles*). The set V_Ts were 300 ml **A**, 500 ml **B**, and 800 ml **C**, as indicated by the horizontal lines. * P <0.05 versus control mechanical condition A. *Horizontal bars* are SD when greater than *rectangles*



than expected for each of the three nominal tidal volumes; Oxylog 2000 and AXR1a delivered more than the set V_T of 300 ml but less than the set V_T of 800 ml. In all other instances, the set V_T wase achieved (Fig. 4).

Effect of mechanical load

Overall, altering the mechanical conditions relative to control load A resulted in decreasing V_T. Condition C achieved the greatest significance except for AXR1a,

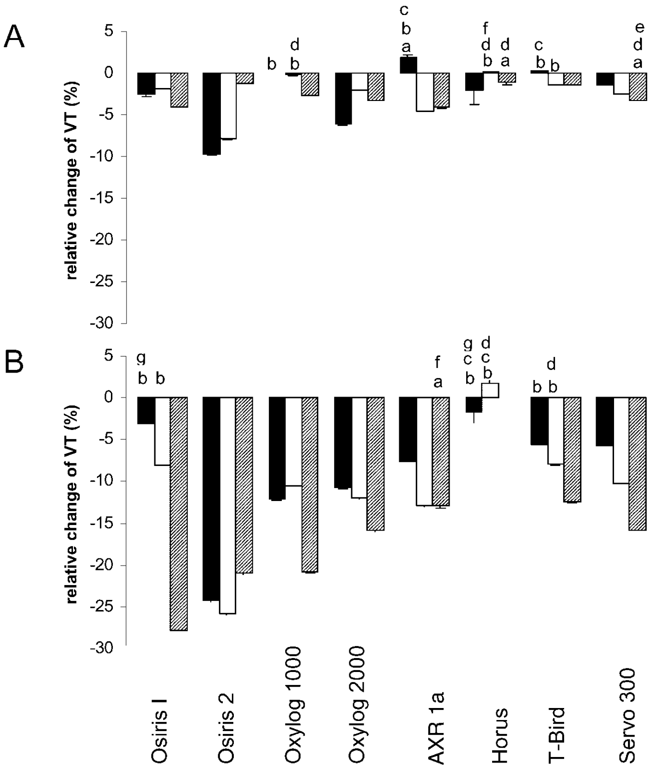


Fig. 5A, B Tidal volume changes relative to control mechanical condition A during mechanical conditions B **A** and C **B** at 300 ml (*black rectangles*), 500 ml (*white rectangles*), and 800 ml (*hatched rectangles*) of set V_T. *P* <0.001: *a* vs Osiris 1, *b* vs Osiris 2, *c* vs Oxylog 2000, *d* vs AXR1a, *e* vs T-Bird, *f* vs SV 300, *g* Oxylog 1000. Symbols are mean values. *Bars* are SD when greater than *rectangles*

Oxylog 2000, and Horus for which a V_T of 800 ml was also less during condition B than during condition A (Fig. 4). This effect was more marked as V_T increased. However, there were some differences between ventilators (Fig. 4). For instance – and with the following all relative to A – the V_T of 300 ml did not significantly change for AXR1a, T-Bird, and Horus, nor did it significantly change for AXR1a and Horus at a V_T of 500 ml, nor for Oxylog 1000 and Osiris 2 at a V_T of 800 ml (Fig. 4). Relative decreases greater than 10% from the control mechanical condition were obtained with: Osiris 1 at a V_T of 800 ml; Osiris 1, Osiris 2, Oxylog 1000, and Oxylog 2000 at the three set V_T; AXR1a at a V_T of 500 ml and 800 ml; and T-Bird and SV 300 at a V_T of 800 ml (Fig. 5).

Ventilator effect

The significant pairwise differences between ventilators are detailed in Fig. 5.

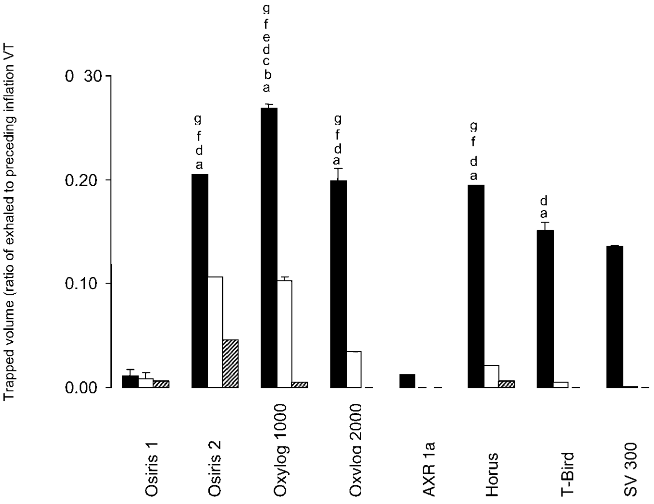


Fig. 6 Trapped volume values, an index of expiratory resistance of the valve and circuit of the different ventilators at expiratory times of 0.7 s (*black rectangles*), 1 s (*white rectangles*), and 1.4 s (*hatched rectangles*). *P* <0.001: a vs Osiris 1, b vs Osiris 2, c vs Oxylog 2000, d vs AXR1a, e vs T-Bird, f vs SV 300. Symbols are mean values. *Bars* are SD when greater than *rectangles*

Trapped volume

A significant interaction between ventilatory rate and ventilator was found. Each of these two factors had a significant effect on the trapped volume values (Fig. 6). Therefore, the trapped volume values were compared between ventilators at each level of ventilatory rate. A striking difference between ventilators regarding trapped volume during expiration was observed for the faster ventilatory rate of 35 breaths/min, as shown in Fig. 6. Two non-ICU ventilators, Osiris 1 and AXR1a, exhibited very low values of trapped volume compared to any of the other ventilators. At a ventilatory rate of 30 breaths/min, the results tended to be similar though less marked than with the previous expiratory time. The differences were no longer significant between ventilators at a ventilatory rate of 25 breaths/min.

Triggering sensitivity of the inspiratory valves

The various indexes of inspiratory effort required to open the triggering systems of five portable ventilators are shown in Fig. 7.

PEEP Effect

With Oxylog 2000, the values of ΔP, Δt, and PTP were significantly greater with PEEP than with ZEEP for both levels of inspiratory effort. Contrary findings were observed with Horus and Osiris 2; the greater the PEEP the

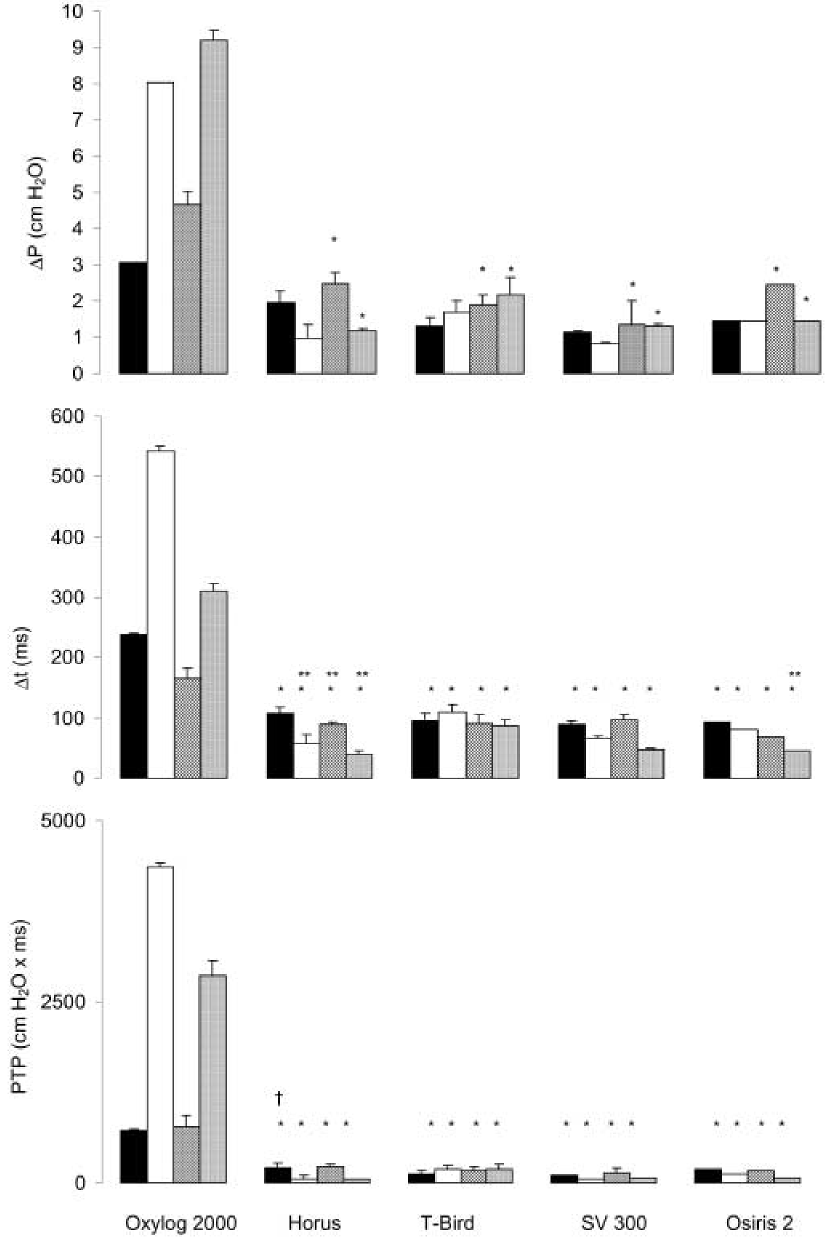


Fig. 7 Performance of the triggering systems of five ventilators assessed with normal inspiratory effort with PEEP 0 (*black rectangles*) and PEEP 5 (*white rectangles*) and with a strong inspiratory effort with PEEP 0 (*hatched rectangles*) and PEEP 5 (*dotted rectangles*). * P <0.001 vs Oxylog 2000, ** P <0.001 vs T-Bird, † P <0.001 vs SV 300. Symbols are mean values. *Bars* are SD when greater than *rectangles*

lower the inspiratory effort. Similar results were also obtained with SV 300, significance being reached only for normal inspiratory effort. Finally, with T-Bird, no significant difference was found between ZEEP and PEEP for any of the three indexes.

Ventilator effect

The multiple comparison procedure showed that the mean values of ΔP with Oxylog 2000 were significantly greater than those obtained with the other ventilators whatever the level of the other two factors (Fig. 7). For Δt and PTP, the results were similar, Oxylog 2000 exhibiting the greatest values of both variables (Fig. 7).

Discussion

The main findings of this study were that: 1) V_T delivery was better achieved with the three ICU ventilators than with any of the portable ventilators; 2) the lowest trapped volume was obtained with two portable ventilators; 3) the triggering system performance was poor for Oxylog 2000 but good or excellent for Osiris 2 and the three ICU ventilators; and 4) performance was more ho-

Table 2 Five-point scale league-table analysis of the performance of the ventilators. (*1* poor, *2* moderate, *3* intermediate, *4* good, *5* excellent, *ND* not done)

	Osiris 1	Osiris 2	Oxylog 1000	Oxylog 2000	AXR1A	Horus	T-Bird	SV 300
V_T delivery	1	1	3	1	2	5	4	4
Trapped volume	5	2	1	2	5	2	3	4
Triggering system	ND	4	ND	1	ND	4	4	5

mogenous among the ICU ventilators than among the portable ventilators (Table 2).

Before discussing these results, a critique of our methods is required. The model we used is well-suited for evaluating the pneumatic characteristics of the ventilators, that is, their ability to deliver a given V_T while compliance and/or resistance of the lung are changed. The advantage of the model is that mechanical alterations can be standardised and reproduced. In addition, the test lung was modified to simulate spontaneous breathing [8]. Hence, the different machines were tested under similar conditions during both static and dynamic experiments. However, it is clear that these laboratory conditions are not real life, so the results of these bench studies should be extrapolated to patients with caution. Therefore, this bench study should be completed by a clinical evaluation of the effects of the ventilators, for instance, on gas exchange during patient transportation. Our study does not include this. In addition, we have only tested a single device and therefore the variability between ventilators was not assessed. Finally, the accuracy of the alarms for the different parameters was not investigated.

Tidal volume delivery

The desired V_T was imperfectly delivered under the baseline condition from four portable ventilators. V_T was not directly adjusted but calculated from the ratio of minute ventilation to ventilatory rate in the cases of Osiris 1, Oxylog 1000, and AXR1a. Surprisingly, the V_T of 300 and 800 ml were not adequately delivered from Oxylog 2000, even though a direct adjustment of V_T was possible via the continuous measurement of expired V_T. We cannot exclude operator bias during manipulating the control knob even though full attention was given to this during setting. In addition, the manufacturer's claim that errors in delivering V_T may be as high as 20% and 10% from Oxylog 1000 and 2000, respectively. With mechanical condition B (increased resistance and reduced compliance), the delivery of V_T was reduced relative to the baseline condition in almost all cases. These changes were neither statistically nor clinically significant, thus V_T delivery from these ventilators remained good under this condition which simulates the pattern of respiratory mechanics commonly observed in acute respiratory failure in ICU [9, 10, 11]. However, with the extreme condition C, during which resistance was markedly increased, the reduction of V_T from the portable ventilators was clinically relevant inasmuch as the set V_T was greater (Figs. 4 and 5). This reduction can be explained by three factors. First, these portable ventilators are equipped with a Venturi-flow generating device. With increasing R, the amount of flow entering a Venturi device decreased which resulted in a decrease in the total flow from the ventilator. Second, these ventilators are pressure-limited so that once a predetermined level of peak airway pressure is reached, inflation continues but at a lower pressure [7]. However, we did not observe this, probably as a result of the Venturi limitation mentioned above. Third, the portable ventilators did not compensate for the compliance of the circuit because they did not include a feedback system able to regulate a proportional valve from a volume signal during inspiration. However, SV 300 does offer this. The ICU devices are not Venturi-equipped. Horus was able to adequately deliver a V_T of 500 ml but not one of 800 ml. This was probably due to the combination of a very high inflation flow leading promptly to the maximal pressure and a pressure limit set at 90 cmH_20. The inflation was then interrupted after the first 300 ml and the expiratory valve opened. With the T-Bird and SV 300 ventilators, under condition C, the delivered V_T dropped by 12% and 16%, respectively, relative to control condition A. This was not explained by pressure limitation but rather by an inability to generate optimal inspiratory flow in condition C.

Trapped volume

For measurement purposes, the respective contribution of tubing and the expiratory valve in expiratory resistance was not assessed.. Marked differences between ventilators were observed. The lowest resistances were obtained with Osiris 1 and AXR1a which had the shortest length tubing. At a ventilatory rate of 25 cycles per minute, no significant gas trapping was detected from all the ventilators. This ventilatory rate is relatively uncommon in clinical practice. However, in the recent large trial of small versus high tidal volume in ARDS patients, ventilatory rates up to 35 cycles per minute were used to avoid excessive respiratory acidosis [12]. At these ventilatory rates, it can be seen from Fig. 6 that all the ventilators, except for Osiris 1 and AXR1a, may induce an important amount of gas trapping along with its deleterious effects. It should be noted that our measurements of trapped volume pertained to normal conditions and not to ARDS mechanical ones.

Triggering system

The manufacturers claim that their portable ventilators have a triggering system making it possible to transport patients while maintaining spontaneous breathing. However, the triggering systems are neither adequate nor equivalent between ventilators. We have found, indeed, that both the magnitude and time delay of the pressure triggering system of Oxylog 2000 were extremely high. These values are close to those found in older ventilators [13, 14]. We have no explanation for this result considering that it was obtained with a flow triggering system. Regarding the four other ventilators, no difference was observed for PTP, except for Horus and SV 300 at normal effort with ZEEP. Specifically, the performance of the pressure triggering system of Osiris 2, a new portable ventilator recently released on the market, compared very nicely with the three ICU devices. This is probably explained by the electronic regulation of the inspiratory valve which is very similar to that of the Horus ventilator. The values of Δt and PTP obtained with the SV 300 ventilator were relatively close to those found by Sassoon et al. [15], the differences being attributed to greater inspiratory effort in the latter study.

Overall, the computations carried out based on the data displayed in Table 2 showed that the mean±SD score of 2.3±1.6 for the five portable ventilators was significantly lower than that of 3.9±0.9 for the three ICU ventilators ($P = 0.03$).

In summary, this study showed that the portable ventilators behaved differently from each other in delivering V_T, offering resistance during expiration and activating the triggering system. Specifically, under the experimental conditions described, Oxylog 2000 should not be recommended. Substantial differences were also found between these portable ventilators and the ICU machines which should be taken into account when using these small ventilators during patient transportation.

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