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Comparative bench study of triggering, pressurization, and cycling between the home ventilator VPAP II and three ICU ventilators

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Abstract *Objective:* To compare triggering, pressurization, and cycling of the home ventilator VPAP II with those of three ICU ventilators (Evita 4, Galileo, and Servo 300). *Design and setting:* Two-compartment lung model study in a research laboratory, university hospital. *Methods:* One compartment was driven by an ICU ventilator to mimic "patient" inspiratory effort, while the other was connected to the tested ventilator. Pressure support of 10, 15, 20, and 25 cmH_2O, and inspiratory efforts of 5, 10, 15, 20, and 25 cmH_2O (inspiratory time 1 s) were used in normal, obstructive, and restrictive conditions. Triggering delay (Td), triggering workload, pressurization at 300 and 500 ms, and difference between the "patient's" inspiratory time and that of the ventilator were analyzed. *Results:* No difference was noted in triggering workload between VPAP II, Evita 4, and Galileo while Servo 300 had a lower value. Pressurization at 300 ms on Evita 4 and Servo 300 reached 75% of the ideal value, on Galileo 35%, and on VPAP II 45%. Pressurization at 500 ms on Evita 4 and Servo 300 reached 85% of the ideal value, on Galileo 50%, and on VPAP II 55%. Cycling was delayed in obstructive conditions and premature in restrictive conditions with each of the devices. *Conclusions:* The VPAP II performed as well as one ICU ventilator and less well than two. Home devices for noninvasive ventilation in acute respiratory failure outside the ICU could prove attractive as they are smaller, less costly, and easier to use than ICU machines.

Keywords Mechanical ventilation · Noninvasive ventilation · Pressure support · Home ventilation · Patient-ventilator interaction

Introduction

During the past decade noninvasive ventilation (NIV) has emerged as the technique of choice in the treatment of both hypercapnic and hypoxemic acute respiratory failure [1, 2, 3, 4], with a resultant decrease in hospital morbidity and mortality [1, 5]. Pressure support has become the preferred ventilatory mode for NIV in the acute setting [4], mainly because of its unique characteristics of adjustable level of respiratory muscle unloading [6] and synchronization with the patient's respiratory pattern [7, 8]. However, optimal patient-ventilator synchronization is often difficult to obtain, especially in patients with altered respiratory system mechanics [8, 9], an important issue given that patient intolerance to NIV is an independent predictor of failure of the technique [5]. One of the key factors determining optimal patient-ventilator interactions is the performance and technical characteristics of the ventilator used [10], an element which has gained more importance nowadays, since NIV can be performed with either ICU ventilators [2] or machines designed for chronic long-term home ventilation [11]. Indeed, the former are more powerful and have more adjustable features (trigger type and sensitivity, slope of

pressurization, cycling criteria) and monitoring capabilities, their downside being cost, size, and knowledge required for their safe use, while the latter are small, portable, easier to use, and less costly but often lack power, fine tuning of settings, and monitoring capabilities [12]. Hence making the right choice of ventilator for NIV in the acute setting has become an even more complex issue.

The purpose of the present bench model study was to compare the performance of a new home ventilator, which was used with favorable results in a recent randomized study on NIV [11], with that of three modern ICU ventilators.

Materials and methods

Ventilators tested

The home ventilator VPAP II (ResMed, North Ryde, Australia) is a portable bilevel pressure device with a turbine-type blower capable of delivering a high inspiratory flow rate (>100 l/min), whose spontaneous ("S") mode bears all the characteristics of pressure support: inspiratory flow triggering of pressure support, adjustable pressurization rate, and inspiratory:expiratory cycling based on a fixed value of inspiratory flow. Maximum level of pressure support and minimum positive end-expiratory pressure (PEEP) levels are 25 and 2 cmH_2O, respectively. Additionally, minimal and maximal duration of inspiration can be set. The ICU ventilators studied, widely used in European ICUs, were the Evita 4 (Drägerwerk, Lübeck, Germany), Galileo (Hamilton Medical, Rhäzuns, Switzerland), Servo 300 (Siemens-Elema, Solna, Sweden). The option was taken of using three machines rather than one to allow a more widespread interpretation of the results given the diversity of ICU ventilators available. The specific aspects of pressure support for each machine are summarized in Table 1. All ICU ventilators were set to inspiratory flow trigger, adjusted to obtain maximum sensitivity to inspiratory effort without the occurrence of autotriggering. The VPAP II has a flow trigger whose sensitivity is nonadjustable. Slope of pressurization was set to maximum ("fast ramp") on all machines, i.e., 0 ms for the VPAP II, Servo 300, and Evita 4 and 25 ms for the Galileo.

The main cycling criterion on all machines tested is based on inspiratory flow dropping to a certain percentage of its peak inspiratory level. This cutoff percentage is a fixed value on all machines, except on the Galileo on which it is adjustable. To avoid the risk of major premature or delayed cycling ventilators have secondary cycling criteria, which are the following:

- Evita 4: interruption of pressure support if airway pressure rises to more than 2 cmH_2O above the set level of pressure support and/or maximum tidal volume reached.
- Galileo: cycling after an inspiratory time of 4 s.
- Servo 300: when pressure support is set, the clinician must also set the respiratory rate knob, even if controlled breaths are not active, which determines a respiratory cycle duration. If during pressure support inspiration lasts for more than 80% of this total cycle duration, pressurization is interrupted.
- VPAP II: setting of minimum and maximum pressurization times.

Our tests were based on the main cycling criterion, since secondary criteria usually require a clinically based approach, based on witnessed patient-ventilator interactions which were not possible in a bench model study. Thus these secondary criteria were set so as not to interfere with the main cycling parameters:

- VPAP II: minimum pressurization time 0.1 s, maximum pressurization time 2.5 s.
- Servo 300: respiratory rate 10/min. Ttot of 6 s for each cycle, thus 4.8 s (80% of 6 s) maximal inspiratory pressure support time.
- Evita 4: maximum tidal volume set at 2000 ml.

The adjustable expiratory trigger on the Galileo was set at the default 25% value to facilitate comparison with the Evita 4.

Test lung model

All ventilators were connected to a test lung model (PneuView AI 2601I TTL, Michigan Instruments, Grand Rapids, Mich., USA; cross-calibrated independently of the manufacturer by Metron, Trondheim, Norway). The test lung consists of two chambers linked by a rigid metal plate. One of the compartments is connected to a "driving" ventilator (Evita 4). This machine, set in pressure control mode, mimics patient inspiratory effort, the magnitude and duration of which can be adjusted by changing the pressure and rate settings. Since the two compartments are linked, inflation of this driving compartment simultaneously inflates the second compartment, which is connected to one of the ventilators being tested. The onset of inflation of this second compartment is detected as an inspiratory effort and triggers a pressure support response by the tested ventilator. Elastance (E) and "airway" resistance (R) of both compartments are adjustable by precision spring-loading and variable cross-section resistors. During all tests E and R settings of the driving compartment were set to normal, while those of the second compartment were set to reproduce normal, obstructive and restrictive respiratory system mechanics. Both the driving and tested ventilator circuits were equipped with a pneumotachograph and pressure transducer (Biopac Systems, Goleta, Calif., USA). Data acquired online from the pressure-time and flow-time curves, sampled at 2000 Hz, were stored in a laptop computer for subse-

Table 1 Main characteristics of ventilators tested

	Inspiratory trigger	Pressurization phase t in pressure suppor	Main inspiratory: expiratory cycling criteria[a]
VPAP II	Fixed flow trigger	Duration adjustable from 0–200 ms	Fixed
Evita 4	Adjustable flow and pressure trigger	Duration adjustable from 0–200 ms	Fixed, 25% of peak inspiratory flow
Servo 300	Adjustable flow or pressure trigger	Adjustable pressure ramp slope (0–10% of maximum inspiratory time)	Fixed, 5% of peak inspiratory flow
Galileo	Adjustable flow or pressure trigger	Duration adjustable from 25–200 ms	Adjustable, 10–40% of peak inspiratory flow

[a] For secondary cycling criteria, see "Materials and methods"

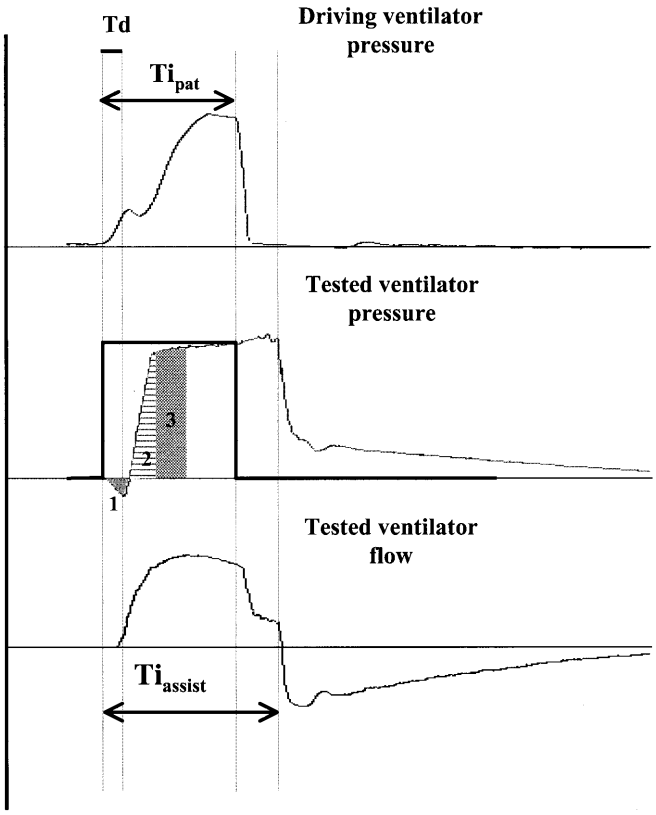


Fig. 1 Pressure-time tracing for driving (*upper tracing*) and pressure- and flow-time tracing for tested (*middle, lower tracings*) ventilators. *Thick line* Ideal pressure support profile; *Td* trigger delay, time between start of inspiratory effort and the onset of pressurization; Ti_{pat} duration of "patient" inspiratory effort; Ti_{assist} duration of mechanical inspiratory assistance; *PTPt* inspiratory trigger pressure-time product (*area 1*), the area under the pressure-time curve between the beginning of pressure support to the point of return to atmospheric pressure or PEEP; PTP_{300} pressure-time product 300 ms after the onset of inspiratory effort (=*area 2 – area 1*); PTP_{500} pressure-time product 500 ms after the onset of inspiratory effort (*area 3 + area 2 – area 1*). PTP_{300} and PTP_{500} are expressed as a percentage of ideal PTP (determined by computing the same areas using the ideal pressure-time curve)

quent analysis (AcqKnowledge software, Biopac Systems, Santa Barbara, Calif., USA).

Measured variables

The three main determinants of patient-ventilator synchronization, i.e., inspiratory trigger, pressurization ramp, and inspiratory:expiratory cycling were evaluated, as illustrated in Fig. 1. For each determinant specific parameters were computed:

Inspiratory trigger

We measured triggering delay (Td), the time from onset of inspiratory effort to the start of detectable pressurization, and inspiratory trigger pressure-time product (PTPt), the area under the pressure-time curve between the beginning of pressure support to the point of return to atmospheric pressure or PEEP. We considered that the end of the pressure decrease in the circuit resulting from the inspiratory effort corresponded to the moment when the ventilator started pressurization. Hence Td comprises the delay in detecting patient inspiratory flow by the flow trigger, the delay in inspiratory valve opening, and the delay linked to overcoming the decrease in pressure entailed by inspiratory effort. PTPt is a validated parameter [12] reflecting the inspiratory workload required to trigger the ventilator, high values of PTPt indicating high inspiratory workload.

Pressurization

Pressure-time products at 300 (ms PTP_{300}) and 500 ms (PTP_{500}) after the onset of inspiratory effort were determined by computing the area under the pressure-time curve at these time points. These two variables, which evaluate the ability for the ventilator to pressurize the airways and maintain pressurization during the inspiratory phase [12, 13], are influenced by both the performance of the ventilator and the magnitude of inspiratory effort. Thus values are given as a percentage of the ideal time-pressure curve, as exemplified in Fig. 1.

Inspiratory:expiratory cycling

The duration of mechanical assistance by the ventilator (ti_{assist}) is compared to the simulated patient's inspiratory time (ti_{pat}). The difference between the two (Δti) is expressed as a percentage of ti_{pat}, as $\Delta ti=[ti_{assist}-ti_{pat})/ti_{pat}]\times 100$. Positive values reflect an excessive duration of mechanical assistance by the ventilator (delayed cycling) negative values insufficient mechanical assistance time (premature cycling).

All measurements were performed in ATPS conditions. Automatic BTPS compensation was disabled on the Evita 4, and other ventilators were calibrated in ATPS conditions. Gas compressibility was not taken into account, as its quantitative contribution is negligible in the conditions of our tests [14].

Experimental protocol

All the above parameters were determined from time-pressure curves for levels of pressure support of 10, 15, 20, and 25 cmH_2O, and inspiratory efforts of 5, 10, 15, 20, and 25 cmH_2O. An inspiratory effort of 5 cmH_2O is sufficient only to trigger the ventilator and thus has no effect on the pressurization phase, while a 25 cmH_2O effort tests the ability of the ventilator to cope with a high patient inspiratory demand. Duration of inspiratory effort was set at 1 s and remained constant for all experiments. To ensure comparability between machines in view of the minimum expiratory positive airway pressure (EPAP) of 2 cmH_2O on the VPAP II a PEEP (EPAP on the VPAP II) of 2 cmH_2O was set for all tests on all ventilators. Furthermore, the level of pressure support was adjusted to take into account the fact that ICU ventilators usually provide pressure support above set PEEP, whereas the VPAP II provides pressure support including PEEP. Thus, when comparing for instance 10 cmH_2O pressure support level with 2 cmH_2O PEEP, pressure support was set at 10 cmH_2O on the VPAP II and 8 cmH_2O on the ICU ventilators. The reported tested level of pressure support tested is that set on the VPAP II.

The variable of Δti was measured at 10 cmH_2O inspiratory effort and 20 cmH_2O pressure support in normal (E=20, R=5.6), obstructive (E=20, R=21.6; E=20, R=26.2), and restrictive (E=30, R=5.6; E=50, R=5.6) conditions (elastance measured in $cmH_2O\ l^{-1}$, resistance in $cmH_2O\ l^{-1}\ s^{-1}$). These values of pressure support and inspiratory effort were used to ensure comparability between machines, since with the VPAP II pressure support higher

than 20 cmH_2O is erratic, while pressurization rate for inspiratory efforts higher than 10 cmH_2O often proves insufficient.

For all conditions ten measurements were obtained and averaged. Comparative statistics relied on the Kruskal-Wallis one-way analysis of variance on ranks. Statistical significance was set at $p<0.05$.

Results

Inspiratory trigger

Trigger delay

Td was less than 100 ms for all ventilators at all conditions tested (Fig. 2A). Overall the Galileo and VPAP II were comparable, while the Evita 4 had a shorter Td than either of these machines, and the Servo 300 had the shortest Td of all. On none of machines was Td affected by the magnitude of inspiratory effort or the level of pressure support. Td decreased when level of pressure support was increased only on the Servo 300.

Inspiratory trigger pressure-time product

No difference was noted between the VPAP II, Evita 4, and Galileo while the Servo 300 exhibited a significantly lower PTPt (Fig. 2B). On all machines except the Servo 300 PTPt rose as inspiratory effort increased (Fig. 2C), but it was unaffected by the level of pressure support on all ventilators.

Pressurization

Pressurization after 300 ms

On both the Evita 4 and the Servo 300 the PTP_{300} reached 75% of its ideal value under all test conditions. The Galileo and VPAP II attained only 35% and 45% of this ideal target, respectively (Fig. 3A), no significant difference being noted between these two ventilators. PTP_{300} was not affected by the magnitude of inspiratory effort with the Evita 4 and the Servo 300, but it de-

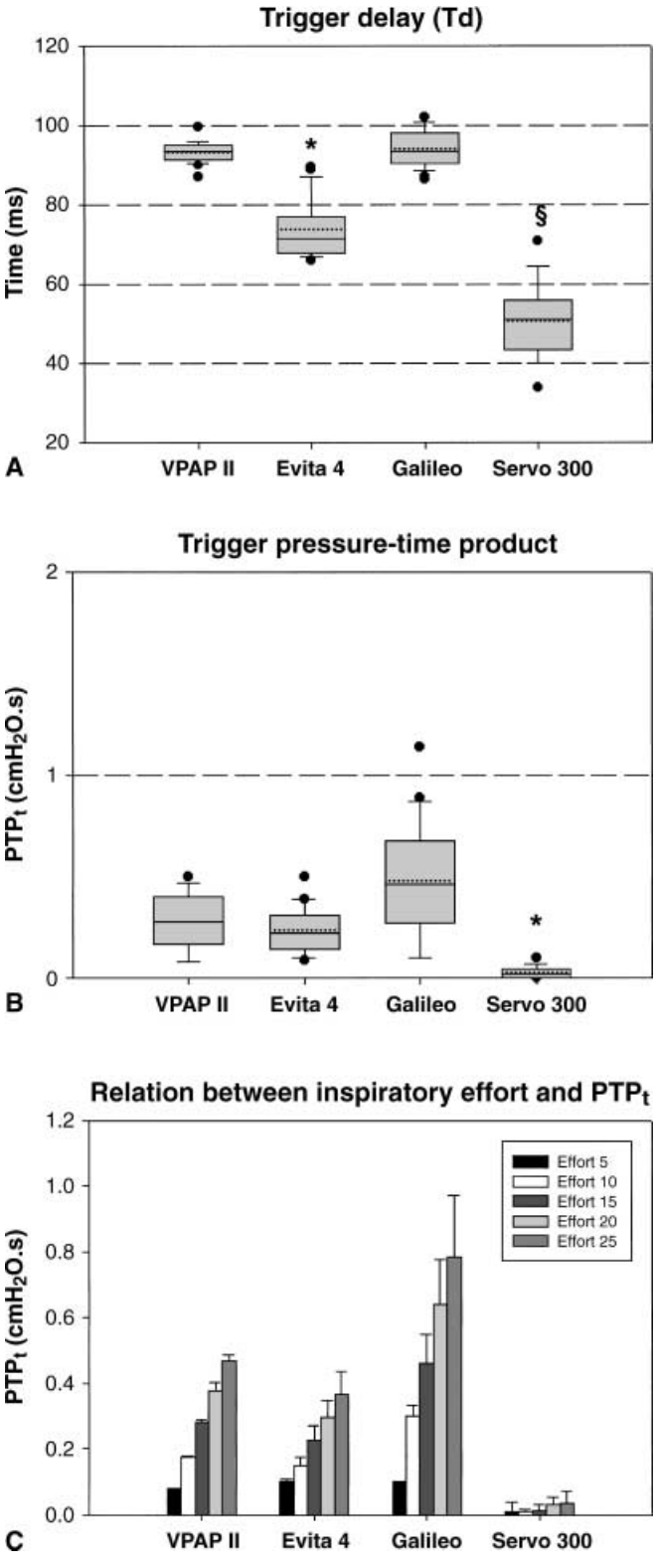
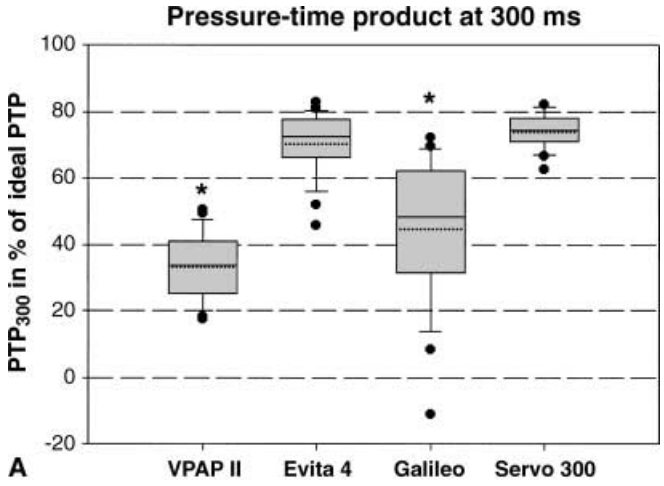
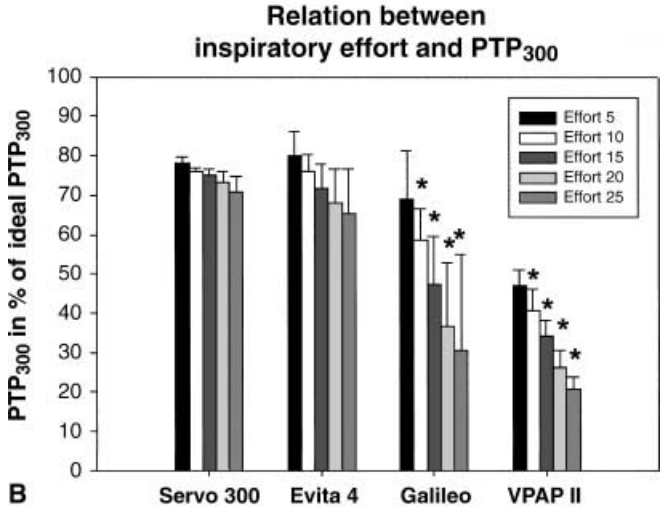
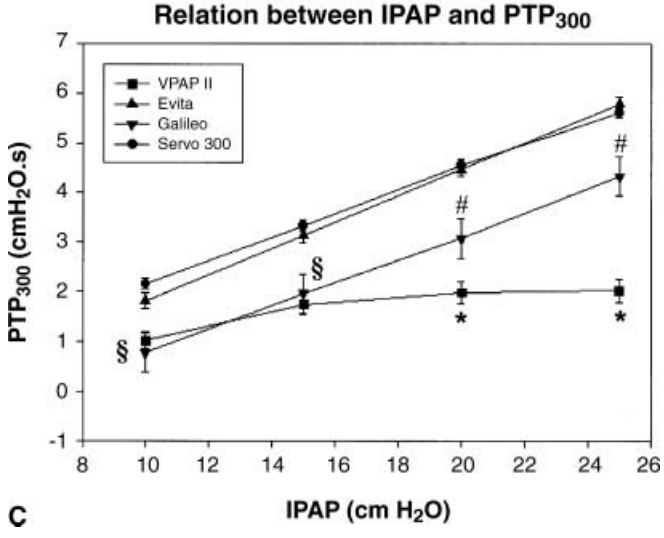


Fig. 2 **A** Trigger delay (*Td*) from pooled data of all experimental conditions. Box and whisker plot shows mean and median (*dashed, continuous lines in boxes*, respectively), 25–75 th percentiles (*lower, upper boundaries of boxes*), 5–95 th percentiles (*vertical bars*), and outliers (*dots*). *$p<0.05$ vs. VPAP II, Galileo, and Servo 300; §$p<0.05$ vs. VPAP II, Evita 4, and Galileo. **B** Trigger pressure-time product (*PTPt*) from pooled data of all experimental conditions. Same symbols for box and whisker plot as above. *$p<0.05$ vs. VPAP II, Evita 4, Galileo. **C** Consequences of magnitude of inspiratory effort on trigger pressure-time product (*PTPt*). For all ventilators PTPt at 10, 15, 20 and 25 cmH_2O was significantly different from PTPt at 5 cmH_2O ($p<0.05$)







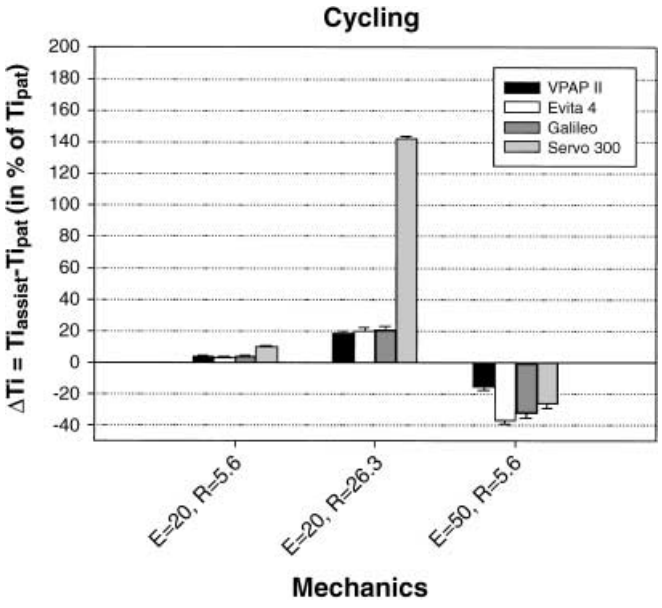


Fig. 4 Difference between the duration of mechanical assistance by the ventilator (ti_{assist}) and simulated patient's inspiratory time (ti_{pat}), expressed in percentage of ti_{pat}, as $\Delta ti=[ti_{assist}-ti_{pat})/ti_{pat}]\times 100$. A positive value for Δti represents excessive duration of mechanical assistance (delayed cycling), while a negative value represents insufficient duration of mechanical assistance (premature cycling). Only one obstructive and one obstructive condition shown. *E* Elastance ($cmH_2O\ l^{-1}$); *R* resistance ($cmH_2O\ l^{-1}\ s^{-1}$). All differences significant ($p<0.05$)

creased as inspiratory effort increased with the Galileo and VPAP II (Fig. 3B). PTP_{300} increased in proportion to the rise in pressure support with all three ICU ventilators while with the VPAP II it reached its maximum at 15 cmH_2O pressure support and failed to increase further as pressure support was increased (Fig. 3C).

Pressurization after 500 ms

On both the Evita 4 and the Servo 300 the PTP_{500} reached 85% of its ideal value under all test conditions while the Galileo and VPAP II attained only 50% and 55% of this ideal target, respectively.

Fig. 3 **A** Pressure-time product at 300 ms (PTP_{300}), expressed as a percentage of ideal value (see Fig. 2 legend), from pooled data of all experimental conditions. *$p<0.05$ vs. Evita 4 and Servo 300. **B** Consequences of increasing magnitude of inspiratory effort on pressure-time product at 300 ms (PTP_{300}). *$p<0.05$ vs. inspiratory effort 5 cmH_2O. **C** Consequences of increasing level of pressure support on pressure-time product at 300 ms (PTP_{300}). *$p<0.05$ vs. Galileo, Evita4, and Servo 300. §$p<0.05$ VPAP II vs. Servo 300 and Evita 4. #$p<0.05$ Galileo vs. Evita 4 and Servo 300

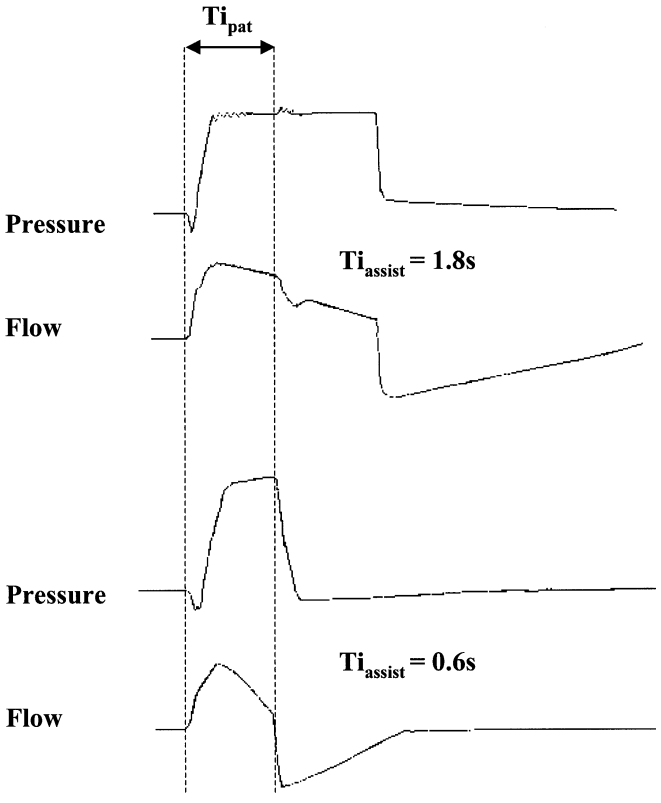


Fig. 5 Representative pressure and flow tracings of delayed cycling in obstructive conditions (*top panel*) and premature cycling in restrictive conditions (*bottom panel*). Ti_{pat} Simulated patient's inspiratory time; ti_{assist} duration of mechanical assistance by the ventilator

Inspiratory:expiratory cycling

With normal respiratory mechanics, the duration of inspiratory assistance on all four ventilators was well synchronized with that of inspiratory effort (Δti of 10%; Figs. 4 and 5). Delayed cycling occurred in obstructive conditions, with a Δti ranging from 15% to 20% with the Evita 4, Galileo, and VPAP II and reaching 140% with the Servo 300. Conversely, cycling occurred prematurely on all machines in restrictive conditions, with a Δti ranging between –15% and –30%.

Discussion

This bench model study determined the following: (a) Triggering delay is less than 100 ms on all machines tested. (b) The inspiratory workload required to trigger the ventilators is very low on these ventilators, the lowest value being measured in the Servo 300. (c) The best characteristics of the pressurization phase were obtained with the Evita 4 and Servo 300 under all conditions tested. The Galileo and VPAP II exhibited comparable pressurization characteristics up to 20 cmH_2O pressure support, the former being at a clear advantage at higher levels of pressure support. (d) All ventilators displayed satisfactory inspiratory:expiratory cycling with normal respiratory mechanics, cycling being delayed in obstructive conditions and premature in restrictive conditions. Delayed cycling with obstructive disease was most marked with the Servo 300 while premature cycling in restrictive disease was most pronounced with the Evita 4 and Galileo.

Before discussing these results, let us briefly comment on the characteristics and limitations of the model used in this study. The obvious limitation is that a bench model cannot truly represent the complex mechanical properties of the human respiratory system, nor can patient inspiratory effort be modeled in a totally realistic fashion. Furthermore, extrapolation of these to the setting of NIV should be taken cautiously. Indeed, our system is leak-free, a choice made to ensure more easily reproducible results, whereas NIV is associated with leaks around the mask that vary with time and can markedly influence the working principles of pressure support, among which the inspiratory flow profile, and cycling. Thus such a model might not allow predictions of ventilator performance in the clinical setting, especially during NIV. Nonetheless, the two-compartment mechanical lung is a validated model used by other investigators for ventilator benchmarking [12, 13, 15] and for studying the effects using helium-oxygen gas mixture on ventilator performance [14].

Regarding the indices used, Td and PTPt are accepted and validated parameters of triggering phase evaluation [12, 13, 15]. The quality of pressurization was assessed by PTP at 300 and 500 ms rather than over the entire duration of inspiration for two reasons. First, inspiratory flow rate is maximal during the first 250–300 ms of pressurization. Second, for all ventilators tested the set level of pressure support is reached within 500 ms, regardless of the magnitude of inspiratory effort [16]. Thus these two measurements accurately reflect events occurring during the initial portion of pressurization and allow a precise evaluation of both the capacity of the ventilator to meet the patient's inspiratory demand and the machine's ability to reach its target pressure support level. Finally, indirect validation of our results is provided by the fact that the same performance characteristics for the Evita 4, Galileo, and Servo 300 have been found by other investigators using identical measurement tools [12, 13, 15]. If the figures obtained for PTP_{300} and PTP_{500} are extrapolated to the entire inspiratory phase duration, our results would also concur with those of previous studies [12, 13, 17].

As regards clinical relevance, differences in performance of home vs. ICU ventilators on the same type of model have been shown to bear clinical impact in patients [12].

Since the first generation of the VPAP device was shown in previous tests to lag behind in performance compared to some of the other home ventilation machines [13], the purpose of the study was to compare characteristics of the new VPAP II with that of three ICU ventilators, given that most home devices actually outperformed the ICU ventilator used in that study, making them attractive as potential alternatives to ICU ventilators for NIV in the acute setting when it occurs outside the ICU. Our tests show that the VPAP II represents a considerable improvement over the first generation VPAP. Its inspiratory trigger responds as quickly as the ICU ventilators tested, while its speed of pressurization is equal to that of the Galileo, even at high inspiratory demand, provided the level of pressure support is kept below 20 cmH_2O. At higher levels the proportional solenoid valve of the ICU machines is clearly at an advantage over the turbine-type blower of the home device, as illustrated by our tests.

An interesting and surprising finding was that cycling was well adapted to abnormal mechanical conditions, exhibiting the best (albeit not ideal) overall performance. Since the manufacturer did not reveal the exact cycling algorithm used by the ventilator, the reason for this is not quite clear. We hypothesize that there is a variable cycling target value, which depends on the characteristics of the initial portion of the inspiratory flow curve, itself influenced by respiratory mechanics, thus providing an equivalent of adjustable expiratory trigger. In cases in which this would still prove insufficient, the clinician can set minimal and maximal duration of inspiratory time, allowing further adjustments of cycling. Indeed, limiting inspiratory time could prove useful in obstructive patients to reduce the risk of delayed cycling, while prolonging it could alleviate premature cycling often witnessed in restrictive patients. In the ICU ventilators cycling occurs when inspiratory flow decreases to a preset value, usually a percentage of peak inspiratory flow (25% in the Evita 4 and default setting in the Galileo, 5% in the Servo 300). A fixed value at which the machine cycles lacks adaptability in the face of changing respiratory system mechanics, with premature cycling occurring in restrictive conditions and delayed cycling in obstruction conditions [18], as confirmed in this study. One solution is to provide an adjustable cutoff cycling value ("expiratory trigger"), which can be either automatic as in the VPAP or set by the user as in the Galileo. The clinical relevance of obtaining a better synchrony between the patient's neural inspiratory time and the duration of the ventilator's mechanical inspiration through adjustable cycling criteria has been illustrated in a study demonstrating its favorable impact on inspiratory efforts and comfort [19].

Given the results of our tests, in which it performed as well as three modern ICU ventilators within certain limits, a home device such as the VPAP II might represent an alternative to the use of an ICU ventilator to apply NIV in acute setting respiratory failure. Indeed, such a machine is smaller, less costly, and easier to use than an ICU ventilator and could thus prove cost-effective in certain settings such as the emergency ward, recovery room, or general ward. Home ventilators, in particular bilevel pressure devices, have already been used successfully to administer NIV in patients without chronic obstructive pulmonary disease [3, 20, 21, 22] and in those with [23, 24, 25]. Furthermore, a recent multicenter trial showing a reduction in intubation rate and hospital mortality in decompensated patients with chronic obstructive pulmonary disease relied on the VPAP II [11].

Several limitations to the use of such devices must nonetheless be kept in mind [13]. First, they cannot administer high inspired O_2 concentrations. Second, they cannot reliably provide high (>20 cmH_2O) levels of pressure support (bearing in mind, however, that most published studies in the NIV literature used levels of 15–20 cmH_2O). Furthermore, as discussed above, pressure support includes the level of PEEP. These two factors could prove to be a limitation in patients with hypoxemic respiratory failure, in whom high levels of FIO_2 and PEEP are required. Third, CO_2 rebreathing can occur with some circuits. Fourth, they often lack monitoring capability.

In conclusion, this study demonstrates that the VPAP II, a device initially designed for home ventilation, can perform as well as three modern ICU ventilators in a lung model study, within certain limits of pressure support. Bearing in mind some of their present limitations, such machines could offer an attractive alternative to ICU ventilators in patients with acute respiratory failure occurring outside the ICU (e.g., the emergency room and the recovery room) due to their small size, low costs, and relative ease of use. Further research should explore their role as first-line ventilators for NIV, and define those patients and settings who are most likely to benefit from their more widespread use.

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