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A M E R I C A N C O L L E G E O F
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laboratory and animal investigations

Performance Characteristics of 10 Home Mechanical Ventilators in Pressure-Support Mode*

A Comparative Bench Study

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Objective: Inspiratory pressure (P_i) support delivered by a bilevel device has become the technique of choice for noninvasive home ventilation. Considerable progress has been made in the performance and functionality of these devices. The present bench study was designed to compare the various characteristics of 10 recently developed bilevel P_i devices under different conditions of respiratory mechanics.

Design: Bench model study.

Setting: Research laboratory, university hospital.

Measurements: Ventilators were connected to a lung model, the mechanics of which were set to normal, restrictive, and obstructive, that was driven by an ICU ventilator to mimic patient effort. Pressure support levels of 10 and 15 cm H₂O, and maximum were tested, with “patient” inspiratory efforts of 5, 10, 15, 20, and 25 cm H₂O. Tests were conducted in the absence and presence of leaks in the system. Trigger delay, trigger-associated inspiratory workload, pressurization capabilities, and cycling were analyzed.

Results: All devices had very short trigger delays and triggering workload. Pressurization capability varied widely among the machines, with some bilevel devices lagging behind when faced with a high inspiratory demand. Cycling was usually not synchronous with patient inspiratory time when the default settings were used, but was considerably improved by modifying cycling settings, when that option was available.

Conclusions: A better knowledge of the technical performance of bilevel devices (*ie*, pressurization capabilities and cycling profile) may prove to be useful in choosing the machine that is best suited for a patient’s respiratory mechanics and inspiratory demand. Clinical algorithms to help set cycling criteria for improving patient-ventilator synchrony and patient comfort should now be developed. (CHEST 2005; 127:1784–1792)

Key words: bilevel ventilation devices; cycling; home ventilation; mechanical ventilation; pressure support

Abbreviations: CC = cycling criterion; E = elastance; NIV = noninvasive ventilation; PEEP = positive end-expiratory pressure; P_i = inspiratory pressure; P_{max} = maximum pressure support; PTP = pressure-time product; PTP₃₀₀ = pressure-time product values at 300 ms; PTP₅₀₀ = pressure-time product values at 500 ms; Raw = airway resistance; T_{assist} = duration of pressurization by the device; T_{ipat} = duration of inspiration set on the driving ventilator

During the last decade, major changes have occurred in the field of home noninvasive ventilation (NIV). First, the number of patients with obesity-hypoventilation syndrome and COPD whose homes are equipped with long-term home NIV devices has been steadily increasing.^{1,2} Second, there

has been a progressive shift from volume-controlled ventilation to pressure-controlled ventilation, mainly because the latter allows the use of ventilators that are smaller, quieter, easier to use, and cheaper.^{1,3} Third, pressure-support ventilation applied with a bilevel pressure generator has become the ventila-

tory mode of choice when pressure control is used in the home setting.^{1,3,4} Fourth, considerable progress has been made in the design, function, and performance of bilevel devices, such that these machines can perform as well as some ICU ventilators.⁵⁻⁷ Therefore, an increasing number of machines has become available on the market, and the physician is often faced with the difficult task of choosing the optimal device for a given patient. Making the right choice is important, since performance and patient comfort vary among devices.⁴ Furthermore, optimizing patient-ventilator interactions, an increasingly recognized issue especially in the presence of restrictive or obstructive respiratory mechanics,⁸ depends on how a given device can be adjusted to meet the challenge.^{8,9} These issues are key to the success of long-term home NIV, patient-ventilator dyssynchrony being one of the documented causes of patient intolerance to the technique.¹⁰ The purpose of the present study was to compare the performance and adaptability to abnormal respiratory mechanics of 10 recently developed bilevel devices that are available in the United States and/or Europe.

MATERIALS AND METHODS

Ventilators Tested

The following 10 newest generation bilevel devices were tested: Synchrony (Respironics; Murrysville, PA); Somnovent (Weinmann; Hamburg, Germany); VPAP II ST and VPAP III ST-A (ResMed; North Ryde, Australia); Moritz ST (MAP; Martinsried, Germany); Knightstar 330 (Tyco-Nellcor Puritan Bennett; Pleasanton, CA); PV 102+ (Breas; Mölnycke, Sweden); VS Integra and VS Ultra (Saime; Savigny le Temple, France); and SmartAir+ (Airox; Pau, France). The main characteristics of the machines are summarized in Table 1. All machines tested were stock models, with no modifications made to them, and all were tested in operating conditions conforming to the specifications of the manufacturer. Each device was tested with the mandatory leak valve provided by the manufacturer.

Test Lung Model

All ventilators were connected to a classic, validated, two-compartment lung model (Pneu View AI 2601I TTL; MI Instru-

ments; Grand Rapids, MI), which has been described in detail in previous studies.^{5,6} Briefly, the model consists of two separate chambers linked by a rigid metal strip. One chamber is connected to an ICU ventilator (Evita 4; Drägerwerk AG; Lübeck, Germany), which is set in the pressure-control mode to mimic patient inspiratory effort. The magnitude and duration of the latter can thus be adjusted by changing the settings on this "driving" ventilator. Because the two chambers are linked, inflation of the first necessarily inflates the second, which is connected to the ventilator being tested. The onset of passive inflation is therefore detected as an "inspiratory" effort by the tested device, which triggers a pressure-support response. The elastance (E) and airway resistance (Raw) of each compartment can be adjusted separately. Thus, the model allows the simulation of various magnitudes of inspiratory effort, types of respiratory mechanics, and tested ventilator settings.

The ventilator circuits connected to each chamber were equipped with a pneumotachograph and pressure transducer (Biopac Systems; Goleta, CA). A three-way stopcock was inserted into the circuit, between the expiratory valve and the lung model, to simulate leaks around the mask during NIV. The leak was measured by connecting a spirometer to the three-way stopcock. The magnitude of the leak varied with the level of pressure support applied, averaging a maximum of 6 to 8 L/min at 10 and 15 cm H₂O of pressure support, respectively. All measurements were performed at a fraction of inspired oxygen of 0.21. The data were acquired online via an analog-digital converter (MP100; Biopac Systems) that sampled at 500 Hz and were stored in a laptop computer for subsequent analysis (Acqknowledge software; Biopac Systems).

Measured Variables

Inspiratory trigger, pressurization ramp, and inspiratory/expiratory cycling were evaluated, as they represent the main determinants of patient-ventilator interaction.⁸ Specific aspects of these three determinants were assessed (Fig 1).

Inspiratory Trigger: The *triggering delay* (Td) is the time between the onset of inspiratory effort and the onset of detectable pressurization. The *inspiratory pressure-time product* (PTPt) is the area under the pressure-time curve between the onset of inspiratory effort and the return to atmospheric pressure or the set positive end-expiratory pressure (PEEP). PTPt reflects the inspiratory work required to trigger the ventilator; therefore, the lower its value, the smaller the work required of inspiratory muscles.¹¹

Pressurization: The PTPt values at 300 ms (PTP₃₀₀) and 500 ms (PTP₅₀₀) for each respiratory cycle are computed as the area under the time-pressure curve 300 and 500 ms after the onset of inspiratory effort. These two parameters reflect the speed of pressurization and the capacity of the device to maintain the set pressure during inspiratory effort. They depend both on the performance of the ventilator and the magnitude of inspiratory effort, the former being determined by the pressurization ramp and the flow generated by the turbine blower of the device. PTP₃₀₀ and PTP₅₀₀ are expressed as a percentage of the ideal time-pressure product, as shown in Figure 1. The ideal PTPt (100%) is unattainable, since it would imply a Td of zero and instantaneous pressurization by the machine. Nonetheless, the closer the values of PTP₃₀₀ and PTP₅₀₀ are to 100%, the higher the pressurization capacity of the device.

Inspiratory/Expiratory Cycling: The duration of pressurization by the device (T_{assist}) is compared to the patient's actual inspiratory time (*ie*, the duration of inspiration set on the driving ventilator [T_{ip}at]). The difference between the two, ΔT_i, is expressed as a percentage of T_{ip}at, as follows: ΔT_i = (T_{assist} - T_{ip}at)/T_{ip}at - 100. A positive value for ΔT_i reflects a duration of pressur-

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Table 1—Main Characteristics of the 10 Bilevel Devices Tested*

Ventilators	Inspiratory Trigger	Pi _{max}	PEEPmin	PS Slope	Expiratory Trigger
Integra	1–5 AU	30	4	0–3 AU	75% of V _I max, unadjustable
Knightstar	1–5 AU	30	3	0.5–3 AU	18%, 25%, 32%, 44%, and 55% of V _I max
Moritz	5 sensitivity settings	18	4	3 settings	5 sensitivity settings
PV 102+	16–30 AU	30	4	1–3 AU	1–15 AU
SmartAir	1–5 AU	30	4	1–4 AU	25%, 50%, 75%, and 85% of V _I max
Somnovent	1–5 AU	20	4	2 settings	1–5 AU
Synchrony	Automatic	30	4	0.5–3 s	Automatic
Ultra	1–5 AU	30	4	0–3 AU	75% of V _I max, unadjustable
VPAP II ST	Unadjustable	30	2	0–0.9 s	Not specified, unadjustable
VPAP III ST-A	3 sensitivity settings	30	2	0–0.9 s	3 sensitivity settings

*AU = arbitrary units; PEEPmin = minimum level of PEEP that can be set on the device; Pi_{max} = maximum Pi that can be set on the device; PS Slope = possible settings of the slope of pressurization (the lower the number, the steeper the slope); V_Imax = peak inspiratory flow rate.

ization exceeding that of the patient's inspiratory effort (delayed cycling), while a negative value reflects premature interruption of pressurization (premature cycling).

Experimental Protocol

Td, PTPt, PTP₃₀₀, and PTP₅₀₀ were measured, as described above and in Figure 1, at three levels of pressure support (ie, 10 and 15 cm H₂O, and the maximum pressure support [PSmax] level allowed). In bilevel devices, the effective pressure support is the difference between inspiratory pressure (Pi) and PEEP. PEEP was set at the minimal value allowed by each device (Table 1). The minimal PEEP varies from one ventilator to another; therefore, the Pi of each device was set so that the Pi-PEEP difference (ie, the level of actual pressure support delivered by the ventilator) was the same on all devices for the intermediate levels of 10 and 15 cm H₂O. PSmax was different for each ventilator, however, due to the fact that the maximum Pi and the minimum PEEP vary from

one machine to the other (Table 1). The inspiratory trigger was set at the maximum sensitivity without the presence of auto-triggering. The pressurization slope was set to its steepest value. When the inspiratory/expiratory cycling criterion (CC) was adjustable, it was maintained at its default value. The driving ventilator was set as follows: airway pressure release ventilation (ie, pressure control without the possibility for assisted cycles to occur); PEEP, 5 cm H₂O; pressurization ramp, 0.2 s; and plateau pressures, 5, 10, 15, 20, and 25 cm H₂O. The magnitude of inspiratory effort was determined by setting the plateau pressure on the driving ventilator. Indeed, with a constant ramp, the higher the level at which plateau pressure was set, the faster the driving chamber was inflated, which approximately models an increase in inspiratory drive, representing the magnitude of inspiratory effort. A 5-cm H₂O inspiratory effort is just sufficient to trigger the ventilator, and therefore does not influence the pressurization phase. This low value was used to determine the PTPt, in order to eliminate the confounding effect that a higher inspiratory

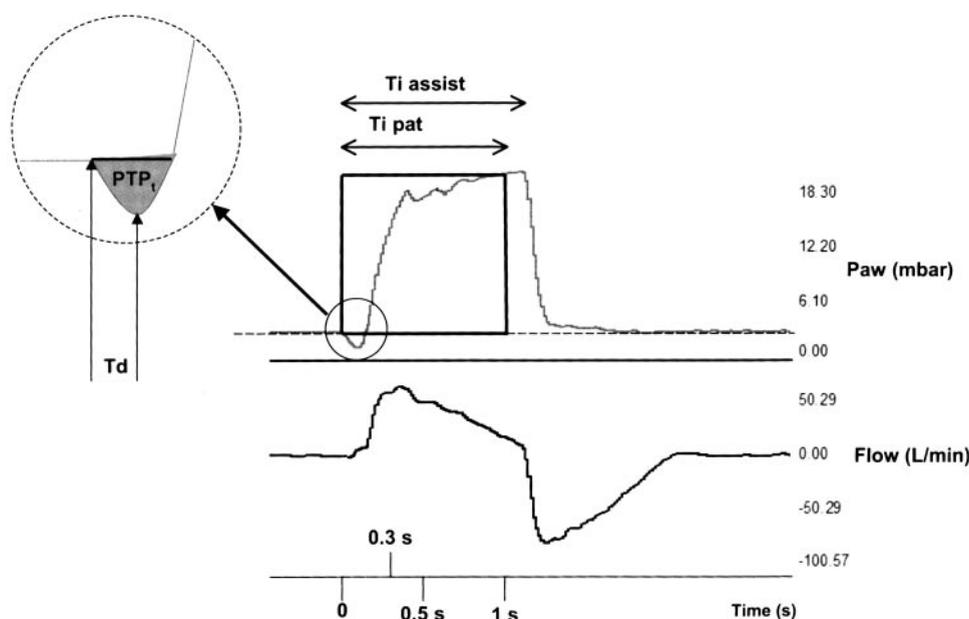


FIGURE 1. Pressure-time and pressure-flow tracings for tested bilevel ventilation devices. PTP₃₀₀ and PTP₅₀₀ are expressed as percentages of the ideal PTPt, which is represented by the square with bold tracing.

effort would have on PTPt. Indeed, with a high inspiratory demand, the PTPt is also influenced by the pressurization performance of the ventilator.^{5,6} At the other end of the spectrum, a 25-cm H₂O effort tests the capacity of the ventilator to generate an inspiratory flow rate that is sufficient to meet a high inspiratory demand. The duration of inspiratory effort on the driving ventilator was set at 1 s for all tests.

During the tests, the E and Raw of the driving chamber were set to 0.02 cm H₂O/mL and 20 cm H₂O/L/s, respectively, which are considered to be normal levels for this model, allowing a fairly rapid return of the test chamber to its resting volume. ΔTi was measured as described above and in Figure 1 for a moderate inspiratory effort (10 cm H₂O), and a pressure support level of 15 cm H₂O in the following respiratory mechanics conditions: normal: E = 20 cm H₂O/L; Raw = 5.6 cm H₂O/L/s; obstructive: E = 20 cm H₂O/L; Raw = 26.2 cm H₂O/L/s; and restrictive: E = 30 cm H₂O/L; Raw = 5.6 cm H₂O/L/s.

The choice of settings used are those that we have found, through experience, to best reflect the mechanical conditions observed in healthy subjects and patients. Since the presence of leaks, which occur very often during NIV, exerts a marked influence on cycling,⁹ ΔTi was tested in the absence and presence of leaks, with the leaks generated by the three-way stopcock technique described above.

Statistical Analysis

For all conditions, 10 measurements were obtained and averaged. All results are expressed as the mean ± SD or median with 95% confidence interval, depending on the parametric or non-parametric distribution of the variables. The results for the individual machines were compared by an analysis of variance on ranks. ΔTi with and without leaks was compared by a *t* test. A *p* value of < 0.05 was considered to be significant.

RESULTS

Inspiratory Trigger

The Td was < 200 ms for all machines. Four devices had a mean Td of < 100 ms (Fig 2).

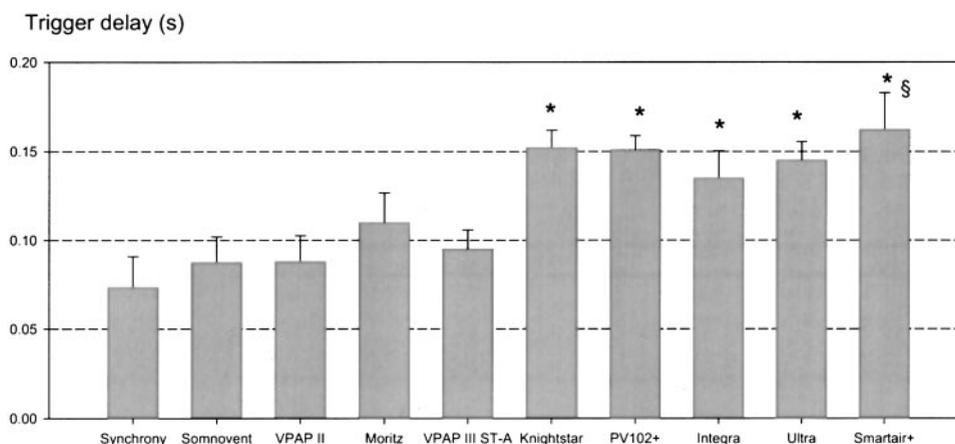


FIGURE 2. Td of the 10 bilevel ventilation devices, tested for an inspiratory effort of 5 cm H₂O. Data pooled for the three levels of pressure support (10, 15 cm H₂O and PSmax). Histogram bars mean ± SD. * = *p* < 0.05 vs the Moritz, Synchrony, Somnovent, VPAP II, and VPAP III ST-A devices; § = *p* < 0.05 vs the Integra and Ultra devices.

For a minimal inspiratory effort, PTPt was very small at each level of pressure support tested (10 and 15 cm H₂O, and the PSmax), and was slightly but significantly higher on one device (Fig 3). The negative pressure deflections preceding the response by the device averaged between 0.7 and 1.2 cm H₂O for all levels of pressure support. With high levels of inspiratory effort, a mean pressure of 4 ± 1 cm H₂O was recorded.

PTP₃₀₀ and PTP₅₀₀

The pressurization capacity varied considerably among devices. At 300 ms, only one machine reached 50% of ideal pressurization (Fig 4), with the other ventilators being distributed into two groups, one in the 30 to 40% range and the other hovering around 20%. At 500 ms, in all conditions tested and for all devices, marked differences were still obvious among ventilators (Fig 5). For all devices, the PTP₃₀₀ and PTP₅₀₀ largely depend on the magnitude of inspiratory effort. As an example, for the Synchrony device, which was the top performer in terms of PTP₃₀₀ and PTP₅₀₀, the PTP₃₀₀ varied between 33% (inspiratory effort, 25 cm H₂O; Pi, 10 cm H₂O) and 56% (inspiratory effort, 5 cm H₂O; and PSmax). The comparative pressure-time curves of the 10 devices at a pressure support level of 10 cm H₂O are shown in Figure 6.

Inspiratory/Expiratory Cycling

Cycling varied markedly among machines, being strongly influenced by the CCs and settings used (Table 2). In the absence of leaks, all ventilators except the Knightstar tended to cycle prematurely with normal respiratory system mechanics, with this tendency increasing the restrictive conditions. Con-

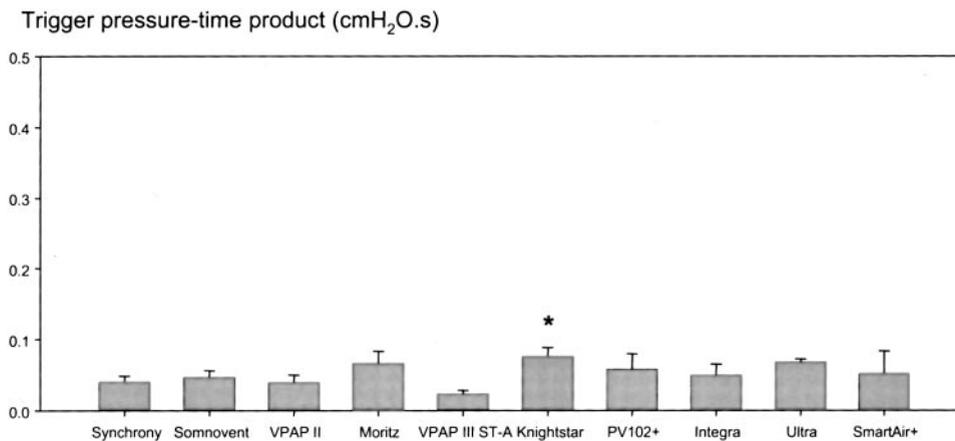


FIGURE 3. Trigger PTPt values for the 10 bilevel ventilation devices tested for an inspiratory effort of 5 cm H₂O. The data were pooled for the three levels of pressure support (10 and 15 cm H₂O, and PSmax). The histogram bars show mean (± SD) values. * = $p < 0.05$ vs the Synchrony, VPAP II, and VPAP III ST-A devices.

versely, the Synchrony, Somnovent, and VPAP III ST-A devices were the best adapted for obstructive conditions. Most other devices, with a few exceptions, exhibiting delayed cycling. In the presence of leaks, an increase in the magnitude of delayed cycling was the most prominent finding on most bilevel ventilation devices. When available, however, adjustable CCs allowed considerable improvement in both delayed and premature cycling (data not shown), with any true comparison being difficult due to the various settings and algorithms of the different devices (Table 1).

DISCUSSION

The results of our tests highlight the following characteristics of the 10 bilevel ventilation devices:

1. Td was < 200 ms on all machines, with four of the machines having delays of < 100 ms.
2. Even though differences existed among machines, all devices required very little triggering effort (*ie*, low PTPt).
3. Major differences were found between the bilevel ventilation devices in terms of pressurization performance (PTP₃₀₀ and PTP₅₀₀),

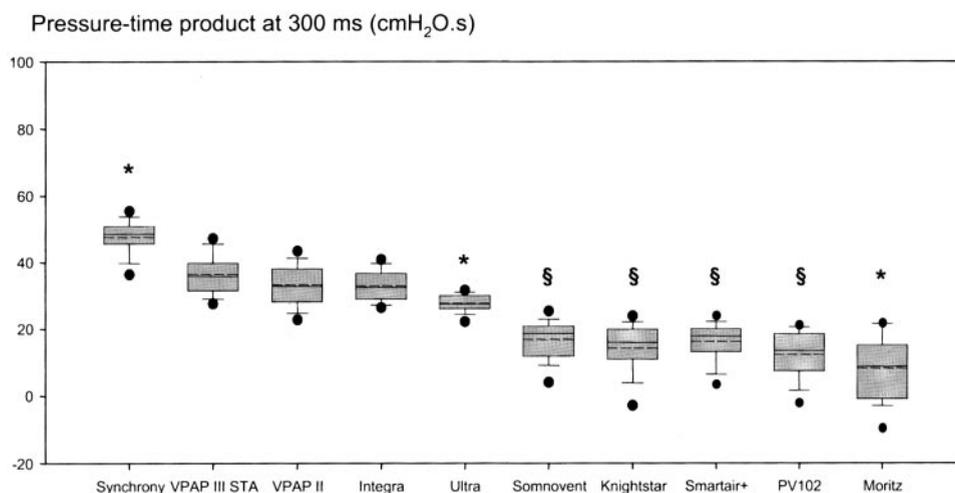


FIGURE 4. PTP₃₀₀ values for the 10 bilevel ventilation devices. The data were pooled for all conditions. Box and whisker plots show the mean values (dashed lines in the boxes), median values (continuous lines in the boxes), 25th to 75th percentiles (vertical bars), and 5th to 95th percentiles (dots). * = $p < 0.05$ vs all other devices; § = $p < 0.05$ vs the Integra, Ultra, VPAP II, and VPAP III ST-A devices.

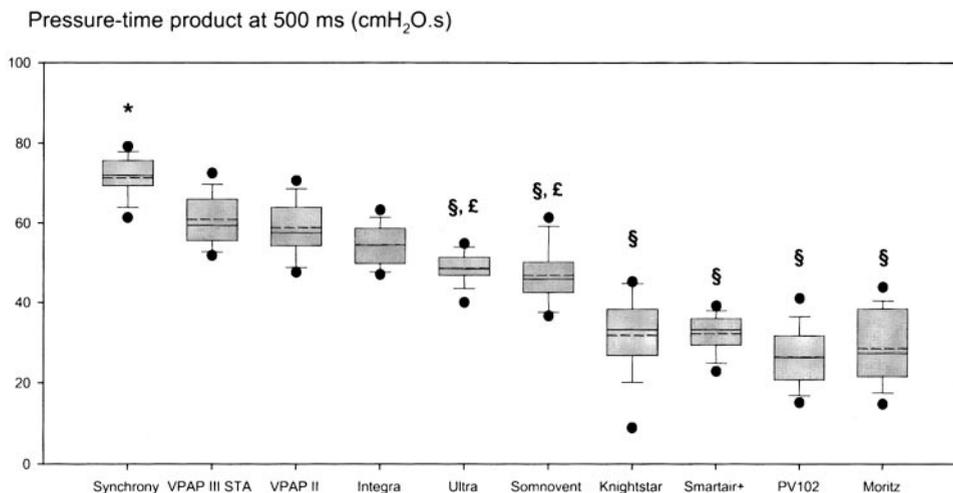


FIGURE 5. PTP_{500} values for the 10 bilevel ventilation devices. The data were pooled for all conditions. Box and whisker plots show the mean values (dashed lines in the boxes), the median values (continuous lines in the boxes), 25th to 75th percentiles (vertical bars), and 5th to 95th percentiles (dots). * = $p < 0.05$ vs all other devices; § = $p < 0.05$ vs the Integra, VPAP II, and VPAP III ST-A devices; £ = $p < 0.05$ vs the Knightstar, Moritz, PV 102, and SmartAir+ devices.

ranging from 0 to 80% of ideal pressurization, especially when a high inspiratory demand was present.

4. Cycling characteristics using the default settings of the ventilators varied somewhat, but in general the machines exhibited delayed cycling under obstructive conditions and premature cycling under restrictive conditions. However, changing the CC setting greatly improved cycling performance on all machines, allowing for such a setting change.

Before discussing these results, a few comments on the features and limitations of the model used should be made. First, the modeling of inspiratory effort by a driving ventilator, although allowing for the adjustment of duration and magnitude, is certainly a simplified and inexact representation of a patient's complex inspira-

tory effort profile. Second, the leak created varied from 8 to 10 L/min, which might not reflect true life conditions. Indeed, NIV is always associated with leaks, the variable magnitude of which can influence the inspiratory flow pattern and cycling, as well as the work of breathing. Third, only some of the determinants of pressure support were tested. However, these have now been shown to reflect various pertinent aspects of the key phases of pressure support and have become a standard in ventilator benchmark testing.^{5-7,11} Fourth, we chose to set the PEEP at its minimum level to ensure that at the PS_{max} level the less powerful machines would not be penalized by an excessive PEEP. This option was also applied at the levels of 10 and 15 cm H_2O PS, although we could have set a standard PEEP on all devices of, for example, 4 or 5 cm H_2O . This option would theoretically have ensured

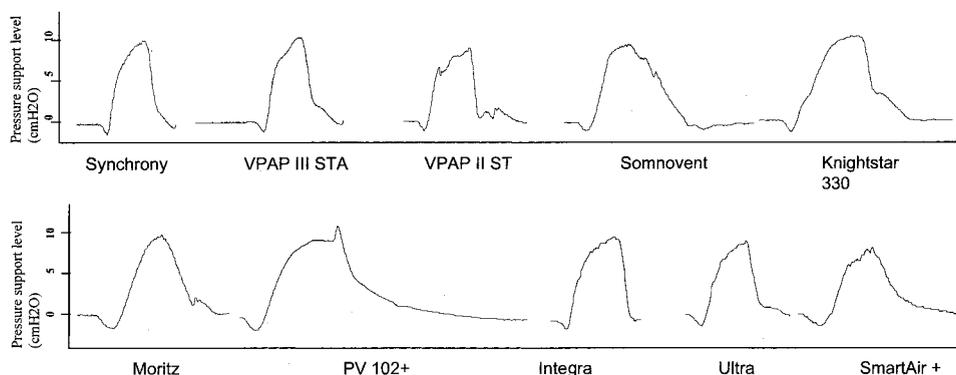


FIGURE 6. Pressure-time curves of the 10 devices at a pressure support level of 10 cm H_2O .

Table 2—Cycling Characteristics of the 10 Bilevel Devices Tested (ΔT_I) in the Presence and Absence of Leaks*

Ventilator	Respiratory System Mechanics					
	Normal		Obstructive		Restrictive	
	No Leak	Leaks	No Leak	Leaks	No Leak	Leaks
Integra	-40.6 ± 1.5	-38.6 ± 0.5	-35.3 ± 0.5	-33.6 ± 2	-43 ± 0.5†	-43 ± 1.7†
Knightstar	32 ± 4	15 ± 1.6§	102 ± 12†	600 ± 0†‡	0 ± 3†	0 ± 0†‡
Moritz	-10.6 ± 4	0 ± 0‡	7.33 ± 3	31.3 ± 5.5†‡	-9.6 ± 5	41.3 ± 7.5†‡
PV 102+	-1.6 ± 2.8	0.6 ± 1.1	53.6 ± 20.5†	47.6 ± 12†	101 ± 5.1†	47.6 ± 12†
SmartAir	-28 ± 3.7	-30 ± 1.7	-15.6 ± 3.2†	-4.3 ± 3.5†	-39 ± 3.6†	-35.6 ± 2.5†
Somnovent	-18.5 ± 0.8	-9.5 ± 2.5‡	5 ± 1†	-17.6 ± 4†‡	-12.6 ± 2†	5.6 ± 1.1†‡
Synchrony	-22 ± 0.57	-19.5 ± 0.5‡	5 ± 1†	7.1 ± 0.7†‡	-32.3 ± 1.52†	-27.5 ± 0.8†‡
Ultra	-37 ± 1.5	-31 ± 1‡	-28 ± 3.2†	-34.6 ± 2.3†	-39 ± 2†	-41 ± 2.6†
VPAP II ST	-17 ± 2.6	-8.3 ± 2‡	12.3 ± 0.5†	31.6 ± 1.5†‡	-24.6 ± 0.5†	-19 ± 1†‡
VPAP III ST-A	-26.6 ± 1.1	-32.3 ± 4.1	-1.6 ± 1.6†	-9.3 ± 2.8†‡	-47.3 ± 2.6†	-50 ± 2.6†

*Values given as mean ± SD. Negative values for ΔT_I reflect premature cycling, while positive values indicate delayed cycling. Values closest to zero indicate optimal cycling. Leaks ranged from 8 to 10 L/min.

†p < 0.05 vs normal mechanics.

‡p < 0.05 vs no leak.

more homogeneous conditions at the 10 and 15 cm H₂O pressure support levels. However, although this might be true in the clinical setting, any difference in bench testing conditions is probably minimal.

Inspiratory Trigger

Our results show that the T_d was very low on the devices tested, and this confirms the improvement of triggering mechanisms that has been observed over the years in mechanical ventilators in general and among bilevel ventilation devices in particular.^{5,6,11} On four of the machines, the T_d was < 100 ms (*ie*, below the conscious threshold of inspiratory effort).¹² This could theoretically contribute to a reduction of dyspnea associated with ventilator triggering, but there is no proof that the 100-ms difference with the other machines has any clinical relevance. Likewise, all devices exhibited low values of PTP_t, which reflects the major improvements brought to such devices over the years.

Pressurization

While the pressurization capacity of the recent generation of bilevel ventilation devices, as assessed by the PTP₃₀₀ and PTP₅₀₀, has been shown to improve and even match that of some ICU ventilators⁵ at low-to-moderate levels of inspiratory demand, ICU machines are clearly at an advantage when facing a high inspiratory demand.^{5,6} Indeed, the proportional solenoid valve of the ICU ventilator is quicker to respond and is more powerful in this type of situation than the turbine-type blower of the bilevel ventilation devices. Nonetheless, since the

earlier studies of the bilevel ventilation devices were performed,^{7,11} our work⁵ and that of others⁶ has shown that there is a clear trend toward an improvement in their overall performance. Regardless, when considering long-term home ventilation, that point is probably not as important as in the acute setting,¹³ as most patients do not have high inspiratory demands, and other factors such as weight, size, and patient comfort are to be considered. Therefore, a bilevel ventilation device should clearly not be chosen on the basis of pressurization performance alone. Nonetheless, in some patients, such as those with marked obesity and severe kyphoscoliosis, the pressurization capacity should be considered, as we have documented¹ that relying on more powerful devices or even volume-controlled ventilators is sometimes necessary to optimize gas exchange and to improve tolerance.

Inspiratory/Expiratory Cycling

It has become increasingly recognized that cycling is an important determinant of optimal patient-ventilator synchrony.⁸ In the pressure-support mode, most ventilators cycle from inspiration to expiration when inspiratory flow decreases to a predetermined fraction of its peak value, which is known as the *expiratory trigger* or CC. A fixed value for the CC can prove to be inappropriate in the presence of abnormal respiratory mechanics, leading to premature cycling in patients with restrictive disease and to delayed cycling in those with obstructive disease, as predicted by a mathematical model,¹⁴ a concept that was recently validated in our laboratory.¹⁵ Cycling asynchrony increases patient discomfort and work of

breathing,¹⁶ but these problems can be attenuated when the CC can be tailored to the patient's respiratory mechanics.^{9,17}

We observed considerable variations in the cycling behavior of the bilevel ventilation devices when used at their default settings (Table 2). As can be seen, at their default settings, most machines tended to cycle prematurely under normal conditions, with the occurrence of premature cycling increasing with restrictive mechanics. Conversely, under obstructive conditions, most devices exhibited delayed cycling. This general pattern was for the most part exacerbated by the presence of leaks. Therefore, at their default settings, some bilevel ventilation devices would appear to be better adapted for use by obstructive patients, while other devices would appear to be better suited for use by patients with restrictive conditions. It should be noted that the Synchrony device has a built-in algorithm (Auto-Trak; Respironics), the features of which automatically improve cycling characteristics. However, most devices allow for the manual adjustment of the CC through various approaches (Table 1), which in our bench tests completely corrected cycling asynchrony. One obvious caveat is that adjusting the CC on the bench model, where mechanical conditions are predetermined and fixed, is quite different from adjusting the CC under clinical conditions in which the patient's respiratory mechanics cannot be measured and are likely to change, as is the magnitude of leaks.⁹ Again, though, changes in respiratory mechanics over time might be less of a concern in stable home-ventilated patients than in those in the acute setting. Nevertheless, discomfort and increased work of breathing related to either premature or delayed cycling may be key factors in patient compliance with treatment and the long-term efficacy of NIV. Thus, as exemplified by the marked variability in cycling characteristics between ventilators and, in a given ventilator, between various conditions of respiratory mechanics, there is a need for simple clinical algorithms to help the clinician adjust the CC to the patient's respiratory mechanics.

CONCLUSION

In a bench model study, 10 recently developed bilevel devices that were designed for home ventilation use exhibited very good triggering characteristics, in terms of both Td and required inspiratory effort. Their pressurization characteristics varied widely, suggesting that some of the devices might be limited in patients with high inspiratory demand (*eg*, in the setting of acute respiratory failure), or for those stable patients with marked obesity or severely

restrictive respiratory mechanics. Finally, most devices when used at their default settings exhibited delayed or premature cycling in the presence of abnormal respiratory mechanics, which could, however, be corrected by manual adjustment of the CC. These results could help clinicians in choosing the appropriate device for use by patients receiving home NIV by tailoring the choice to a given patient's inspiratory profile and respiratory mechanics. Further studies should aim at developing simple methods of assessing optimal patient-ventilator interactions and adjusting CCs to changes in respiratory mechanics.

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REFERENCES

- 1 Janssens JP, Derivaz S, Breitenstein E, et al. Changing patterns in long-term noninvasive ventilation: a 7-year prospective study in the Geneva Lake area. *Chest* 2003; 123: 67–79
- 2 Cuvelier A, Muir JF. Noninvasive ventilation and obstructive lung diseases. *Eur Respir J* 2001; 17:1271–1281
- 3 Schönhofer B, Sonneborn M, Haidl P, et al. Comparison of two different modes for noninvasive mechanical ventilation in chronic respiratory failure: volume versus pressure controlled device. *Eur Respir J* 1997; 10:184–191
- 4 Vitacca M, Barbano L, D'Anna S, et al. Comparison of five bilevel pressure ventilators in patients with chronic ventilatory failure. *Chest* 2002; 122:2105–2114
- 5 Tassaux D, Strasser S, Fonseca S, et al. Comparative bench study of triggering, pressurization and cycling between the home ventilator VPAPII® and three ICU ventilators. *Intensive Care Med* 2002; 28:1254–1261
- 6 Richard JC, Carlucci A, Breton L, et al. Bench testing of pressure support ventilation with three different generations of ventilators. *Intensive Care Med* 2002; 28:1049–1057
- 7 Bumburaphong T, Imanaka H, Nishimura M, et al. Performance characteristics of bilevel pressure ventilators: a lung model study. *Chest* 1997; 111:1050–1060
- 8 Tobin MJ, Jubran A, Laghi F. Patient-ventilator interaction. *Am J Respir Crit Care Med* 2001; 163:1059–1063
- 9 Calderini E, Confalonieri M, Puccio P, et al. Patient-ventilator asynchrony during noninvasive ventilation: the role of expiratory trigger. *Intensive Care Med* 1999; 25:662–667
- 10 Criner GJ, Brennan K, Travaline JM, et al. Efficacy and compliance with noninvasive positive pressure ventilation in patients with chronic respiratory failure. *Chest* 1999; 116: 667–675
- 11 Lofaso F, Brochard L, Hang T, et al. Home versus intensive care pressure support devices: experimental and clinical comparison. *Am J Respir Crit Care Med* 1996; 153:1591–1599
- 12 Whitelaw W, Derenne J, Milic-Emili J. Occlusion pressure as a measure of respiratory center output in conscious man. *Respir Physiol* 1975; 23:181–199
- 13 Plant P, Owen J, Elliott M. Early use of non-invasive ventilation for acute exacerbations of chronic obstructive pulmonary disease on general respiratory wards: a multicentre randomised controlled trial. *Lancet* 2000; 355:1931–1935

- 14 Yamada Y, Du H. Analysis of the mechanisms of expiratory asynchrony in pressure support ventilation: a mathematical approach. *J Appl Physiol* 2000; 88:2143–2150
- 15 Tassaux D, Michotte J, Gainnier M, et al. Expiratory trigger setting in pressure support ventilation: from mathematical model to bedside. *Crit Care Med* 2004; 32:1844–1850
- 16 Parthasarathy S, Jubran A, Tobin M. Cycling of inspiratory and expiratory muscle groups with the ventilator in airflow limitation. *Am J Respir Crit Care Med* 1998; 158:1471–1478
- 17 Chiumello D, Pelosi P, Taccone P, et al. Effect of different inspiratory rise time and cycling off criteria during pressure support ventilation in patients recovering from acute lung injury. *Crit Care Med* 2003; 31:2604–2610

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