Influences of Duration of Inspiratory Effort, Respiratory Mechanics, and Ventilator Type on Asynchrony With Pressure Support and Proportional Assist Ventilation

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BACKGROUND: Pressure support ventilation (PSV) is often associated with patient-ventilator asynchrony. Proportional assist ventilation (PAV) offers inspiratory assistance proportional to patient effort, minimizing patient-ventilator asynchrony. The objective of this study was to evaluate the influence of respiratory mechanics and patient effort on patient-ventilator asynchrony during PSV and PAV plus (PAV+). METHODS: We used a mechanical lung simulator and studied 3 respiratory mechanics profiles (normal, obstructive, and restrictive), with variations in the duration of inspiratory effort: 0.5, 1.0, 1.5, and 2.0 s. The Auto-Trak system was studied in ventilators when available. Outcome measures included inspiratory trigger delay, expiratory trigger asynchrony, and tidal volume (V_T). RESULTS: Inspiratory trigger delay was greater in the obstructive respiratory mechanics profile and greatest with a effort of 2.0 s (160 ms); cycling asynchrony, particularly delayed cycling, was common in the obstructive profile, whereas the restrictive profile was associated with premature cycling. In comparison with PSV, PAV+ improved patient-ventilator synchrony, with a shorter triggering delay (28 ms vs 116 ms) and no cycling asynchrony in the restrictive profile. V_T was lower with PAV+ than with PSV (630 mL vs 837 mL), as it was with the single-limb circuit ventilator (570 mL vs 837 mL). PAV+ mode was associated with longer cycling delays than were the other ventilation modes, especially for the obstructive profile and higher effort values. Auto-Trak eliminated automatic triggering. CONCLUSIONS: Mechanical ventilation asynchrony was influenced by effort, respiratory mechanics, ventilator type, and ventilation mode. In PSV mode, delayed cycling was associated with shorter effort in obstructive respiratory mechanics profiles, whereas premature cycling was more common with longer effort and a restrictive profile. PAV+ prevented premature cycling but not delayed cycling, especially in obstructive respiratory mechanics profiles, and it was associated with a lower V_T. *Key words: artificial respiration; respiratory mechanics; COPD; ARDS; mechanical ventilators.* [Respir Care 2017;62(5):550–557. © 2017 Daedalus Enterprises]

Introduction

Patient-ventilator asynchrony is a mismatch between the inspiratory and expiratory times of the patient and those of the mechanical ventilator, and it is common during assisted ventilation.[1-3] Patient-ventilator asynchrony is associated with complications such as prolonged mechanical ventilation and increased mortality, although it is unclear whether that is a cause-and-effect relationship.[3,4]

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Pressure support ventilation (PSV) is a spontaneous mode of ventilation frequently used during the weaning phase because it allows the patient to influence the duration of inspiratory time and ventilatory assistance.[5,6] However, clinical studies have shown that PSV can result in respiratory distress and patient-ventilator asynchrony.[1,7]

Proportional assist ventilation (PAV) is a ventilatory mode in which the ventilator generates assistance instantaneously and proportional to the effort of the patient, functioning as an amplifier of inspiratory effort and giving the patient greater control over breathing patterns, including tidal volume (V_T), duration of inspiration and expiration, and flow delivery.[8,9] In its more recent version, it is known as PAV plus (PAV+), which automatically estimates the mechanics of the respiratory system and auto-adjusts ventilatory support. Previous studies have shown that PAV+ mode improves patient-ventilator synchrony more than do conventional modes, such as PSV.[10,11] However, cycling off in PAV+ mode employs user-set fixed criteria, which can influence patient-ventilator synchrony.[12]

It is believed that the respiratory mechanics of the patient is one of the factors that influences triggering and cycling in the ventilator.[13-15] However, it is unknown how changes in airway resistance, static compliance of the respiratory system, and the interaction between the two during respiratory muscle contraction affect the degree of patient-ventilator asynchrony in the PSV and PAV+ modalities.[16-18]

We hypothesized that respiratory mechanics and the duration of inspiratory effort would significantly affect patient-ventilator interaction in PSV and PAV+ modes. The aim of this study was to evaluate the influence of respiratory mechanics and duration of inspiratory muscle effort on patient-ventilator asynchrony during PSV and PAV+ ventilation for different models of mechanical ventilators.

Methods

Study Design

This was an experimental study conducted in the Respiration Laboratory of the Department of Internal Medicine at the Federal University of Ceará in Fortaleza, Brazil.

Lung Model

A mechanical model of realistic simulation of mechanical ventilation asynchrony was used. We employed a lung simulator (ASL 5000, IngMar Medical, Pittsburgh, Pennsylvania), simulating predefined combinations of 3 respiratory mechanics profiles and 4 different effort values.[19]

The 3 respiratory mechanics profiles were normal, obstructive, and restrictive.[17,20,21] The profiles studied are

QUICK LOOK

Current knowledge

Patient-ventilator synchrony is a challenge in mechanical ventilation and is associated with complications. Pressure support ventilation is often associated with patient-ventilator asynchrony. Proportional assist ventilation plus offers inspiratory assistance proportional to patient effort.

What this paper contributes to our knowledge

In a lung model study, we demonstrated that mechanical ventilation asynchrony was influenced by the duration of respiratory muscle effort, respiratory mechanics, ventilator type, and ventilation mode. In pressure support ventilation mode, delayed cycling was more common with shorter efforts in the obstructive respiratory mechanics profile, whereas premature cycling was more common with longer efforts in the restrictive profile. The performance of a single-limb circuit portable ventilator was similar to that of conventional ICU ventilators. These patterns of asynchrony were also present in proportional assist ventilation plus mode, although to a lesser degree.

shown in Table 1. The respiratory muscle pressure (P_{mus}) was set at -7.5 cm H_2O, and 4 effort values were configured by using the ASL 5000 software: 0.5, 1.0, 1.5, and 2.0 s. Therefore, the initial inspiration effort was the same for all inspiratory times. This was done to avoid variations in the buildup to the pressure drop or flow that triggers the ventilator. The airway occlusion pressure at 0.1 s was kept constant at -2.5 cm H_2O in all simulations. Consequently, there were 12 scenarios resulting from the combination of 3 respiratory mechanics profiles and 4 effort values. To avoid artifacts and ensure reproducible results, the simulation setup was dismantled and rebuilt at least 4 times in all sets of experiments for each ventilator.

Mechanical Ventilators

Two types of mechanical ventilators were studied: ICU ventilators with dual-limb circuits (Esprit V1000 [Philips Respironics, Murrysville, Pennsylvania]; DX 3012 [Dixtal, Buenos Aires, Argentina]; Evita IV [Dräger, Lübeck, Germany]; Servo-i [Maquet, Solna, Sweden]; and Puritan Bennett 840 [Covidien, Mansfield, Massachusetts]) and a single-limb circuit portable ventilator (Trilogy 100, Philips Respironics). No external humidification system was used. To reproduce the situation of an intubated adult ICU patient, the mechanical ventilators were connected

Table 1. Configuration of the Parameters of the Lung Simulator According to the Respiratory Mechanics Profile

| Profile | Compliance (mL/cm H_2O) | Resistance | | Frequency (cycles/min) |
		Inspiratory (cm H_2O/L/s)	Expiratory (cm H_2O/L/s)	
Normal	60	3	3	15
Obstructive	80	10	20	12
Restrictive	30	8	8	15

Table 2. Inspiratory Trigger Sensitivity and Pressure Rise Time for the Mechanical Ventilators Studied

Ventilator/Mode	Inspiratory Trigger	Rise Time
Esprit V1000	−2 cm H_2O	0.2 s
DX 3012	−2 cm H_2O	Second fastest value
Evita IV	3 L/min	0.2 s
Servo-i	−2 cm H_2O	0.2 s
Puritan Bennett 840	−2 cm H_2O	95 and 100% of the minimum
Puritan Bennett 840, PAV+	−2 cm H_2O	NA
Trilogy 100	3 L/min	Second fastest value
Trilogy 100, Auto-Trak	NA	Second fastest value

PAV+ = proportional assist ventilation plus
NA = not available

to the ASL 5000 simulator using an 8.0-mm endotracheal tube.[16]

All of the ventilators were calibrated and configured in PSV mode, except the Trilogy ventilator, which was set to spontaneous mode. Ventilator parameters were set according to the respiratory mechanics profiles, as follows[1,22]: for the restrictive profile, a PEEP of 10 cm H_2O, pressure support of 13 cm H_2O, and an expiratory trigger of 25% of peak inspiratory flow; for the normal profile, a PEEP of 5 cm H_2O, pressure support of 15 cm H_2O, and an expiratory trigger of 25% of peak inspiratory flow; and for the obstructive profile, a PEEP of 5 cm H_2O, pressure support of 15 cm H_2O, and an expiratory trigger of 45% of the peak inspiratory flow. The PAV+ mode is available only on the Puritan Bennett 840 ventilator. The percentage of support was adjusted to achieve the same mean airway pressure obtained previously in the PSV mode of the same ventilator, and the expiratory flow trigger was set to 3 L/min, as recommended by the manufacturer.[5]

The Trilogy ventilator was used to study the performance of its digital Auto-Trak system for the inspiratory and expiratory trigger. The Auto-Trak system consists of a technology capable of automatically adjusting, breath by breath, the triggering and cycling mechanisms.[23] Table 2 shows the configuration of the rise time and the inspiratory trigger sensitivity, which was set to the minimum value on all ventilators to prevent the occurrence of auto-triggering.[15]

Measurements and Outcomes

The primary outcomes assessed were inspiratory trigger delay and expiratory trigger asynchrony times. Inspiratory trigger delay was defined as the time from the onset of muscle effort (negative deflection of the P_{mus}) to the beginning of the effective supply of inspiratory flow (positive deflection of the flow curve).[16] Expiratory trigger delay was defined as the time from the instant of ventilator cycling to the end of muscle effort (ie, the moment at which the P_{mus} returned to baseline). The expiratory trigger delay was classified as delayed cycling when the ventilator cycled after the end of the effort and as premature cycling when the ventilator cycled before the end of the

effort. Auto-triggering was defined as a cycle delivered by the ventilator without a muscle effort (negative deflection of the P_{mus}), indicating that the ventilator delivered a breath that was not triggered by the lung simulator. The ventilator inspiratory time (T_I) was defined as the time from the start of the delivery of the V_T to the lung simulator to the moment at which the V_T reaches its maximum value.[1,20,24] The V_T and flow values were obtained with the ASL 5000 software (LabVIEW, National Instruments, Austin, Texas), and auto-PEEP values were measured by software analysis of the flow-time curve (see the supplementary materials at http://www.rcjournal.com).

After the mechanical ventilatory support had been stabilized in each experimental setting, 20 representative cycles were collected for offline analysis by the ASL 5000 software. The effective effort and ventilator T_I were measured. The results are presented as means and SD values. Considering the stability of the mechanical model and its almost negligible variability, we chose to make nominal comparisons between the obtained values without conducting comparative statistical tests.[15] The variation in V_T was compared among the mean values obtained with conventional PSV on 5 ventilators (Esprit V1000, DX 3012, Evita IV, Servo-i and Puritan Bennett 840), those measured with the Trilogy ventilator (with and without Auto-Trak), and those obtained in the PAV+ mode of the Puritan Bennett 840 ventilator. Differences that were considered potentially clinically relevant were highlighted and discussed.

Results

We constructed 96 experimental scenarios by combining 8 ventilator modes with 3 types of respiratory mechanics profiles and 4 effort values. Simulation of effort values of 1.5 and 2.0 s in the restrictive profile in PAV+
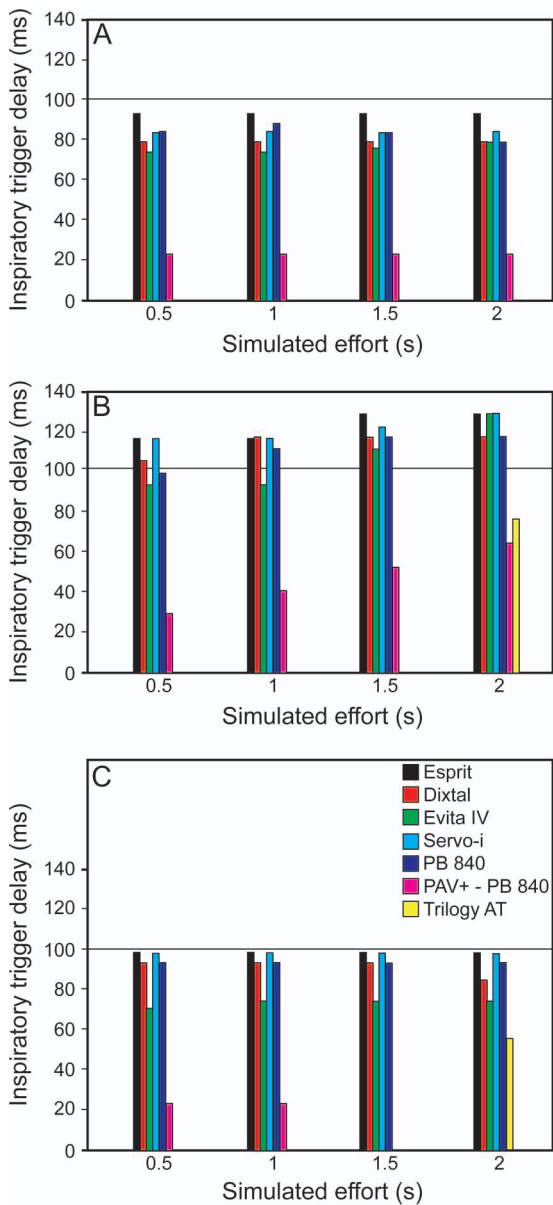
Fig. 1. Inspiratory trigger delay (ms), according to the duration of effort, in normal (A), obstructive (B), and restrictive (C) respiratory mechanics profiles. The horizontal lines mark the 100-ms threshold, which is considered clinically significant. PAV+ = proportional assist ventilation plus, Trilogy AT = Trilogy with Auto-Trak.

mode was not feasible because the ventilator failed to activate that mode in the configuration. It is important to mention that despite the effort configuration in the simulator, we observed that the effective mechanical effort was slightly longer (0.6, 1.07, 1.59, and 2.12 s).

The inspiratory trigger delay was shorter in the normal respiratory mechanics profile than in the obstructive and restrictive profiles, peaking (at 160 ms) in the obstructive profile with a effort of 2.0 s (Fig. 1). The PAV+ mode had

the shortest inspiratory trigger delay. With and without Auto-Trak, the Trilogy ventilator achieved a minimum inspiratory trigger delay at all of the inspiratory times, except in the restrictive and obstructive profiles, for which the Trilogy without Auto-Trak achieved an inspiratory trigger delay only at an inspiratory time of 2.0 s.

The flow waveforms in the PSV and PAV+ modes were recorded for the obstructive and restrictive profiles (Fig. 2). Most of the ventilators did not show significant expiratory trigger asynchrony at effort values of 1.0 and 1.5 s for the normal and obstructive respiratory mechanics profiles, compared with 0.5 and 1.0 s for the restrictive profile (Fig. 3). Expiratory trigger asynchrony (delayed cycling) was predominantly observed in the obstructive profile, whereas premature cycling was mainly seen in the restrictive profile, especially at effort values of 1.5 and 2.0 s.

The PAV+ mode was associated with longer cycling delays than were the other ventilation modes, especially for the obstructive profile and higher effort values. However, the PAV+ mode showed better synchrony at effort values of 0.5 and 1.0 s in the restrictive profile. The PAV+ mode and the 2 Trilogy ventilation modes (with and without Auto-Trak) were associated with V_T values that were lower than those obtained in the PSV mode (Fig. 4).

Discussion

The main outcome measures evaluated in the present study were the effort value, respiratory mechanics profile, ventilation mode, and type of ventilator-influenced mechanical ventilation asynchrony. Prolonged effort increased premature cycling, whereas a shorter effort was associated with delayed cycling, regardless of the type of ventilator or circuit. The obstructive respiratory mechanics profile favored delayed cycling, whereas the restrictive profile was associated with premature cycling, regardless of the ventilator type or mode. Although the PAV+ mode prevented premature cycling in most situations, it was associated with delayed cycling in the obstructive profile. The PAV+ mode also delivered lower V_T values, better inspiratory time synchrony with muscle effort, and shorter inspiratory trigger delay than did PSV. The portable single-limb circuit ventilator showed better inspiratory triggering than did the conventional ICU ventilators.

To our knowledge, this is the first study to specifically address mechanical ventilation asynchrony by evaluating different effort values in the PSV, PAV+, and Auto-Trak function. Some clinical studies have evaluated patient-ventilator asynchrony in subjects with COPD and in those undergoing resolution of ARDS. Such patients might partially correspond to the obstructive and restrictive models used in the present study.[22,25,26] Other investigators have
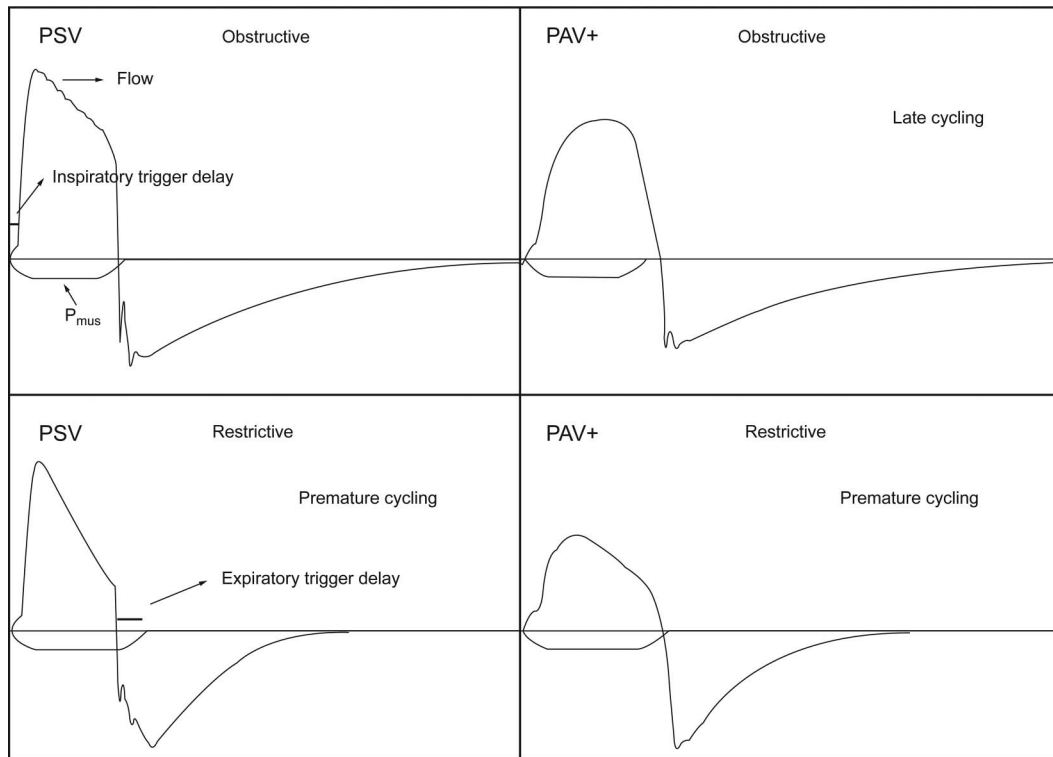
Fig. 2. Representative flow waveforms (in L/min) on the left axis (solid line) and respiratory muscle pressure (P_{mus}, in cm H_2O) on the right axis (dashed line) over time for the pressure support ventilation (PSV) and proportional assist ventilation plus (PAV+) modes in the obstructive and restrictive respiratory mechanics profiles.

found that delayed expiratory triggering (delayed cycling) and ineffective efforts are common during PSV in subjects with COPD[20] and that premature cycling is common in subjects with ARDS, especially at a threshold of 30% of peak inspiratory flow.[26] The results of the present study are concordant with those observational data.[22,26] It is noteworthy that, in our model, delayed cycling occurred in PSV, even when the cycling threshold was adjusted to 45% of the peak inspiratory flow.

During PSV, perfect synchrony occurs only if the effort coincides with the ventilator T_I, which is influenced by the cycling-off criterion.[27,28] In PSV, cycling asynchrony is influenced by respiratory mechanics: The combination of high airway resistance with a short effort predisposes to delayed cycling, whereas restrictive respiratory mechanics with a long effort predisposes to premature cycling. As effort increases, asynchrony tends to switch from delayed to premature cycling, assuming that all other variables remain constant. That phenomenon was clearly demonstrated in our results. The same phenomenon led other investigators to build an algorithm for PSV cycling, in which the cycling-off criterion is periodically readjusted by a closed-loop system instead of being arbitrarily chosen by the operator of the ventilator.[22,29] That algorithm has been tested in a specific ventilator in a small number of subjects.[25] When compared with a fixed cycling criterion

of 5% of peak inspiratory flow, the use of the automatic, real-time-adjusted cycling criterion improved patient-ventilator synchrony.

Clinical comparisons of PSV versus PAV+ have shown that the latter improves patient-ventilator synchrony.[5] In PAV+ mode, cycling asynchrony is less likely to occur, because the cycling criterion is an absolute value of flow, typically 3 L/min, and, as patient effort starts to decrease, flow delivery decelerates; when the cycling criterion is met, the ventilator transitions to exhalation, and premature cycling is avoided in most situations. In the present study, PAV+ prevented premature cycling with normal and obstructive patterns of respiratory mechanics and long effort, whereas PSV did not. The PAV+ mode also delivered inspiratory flow that better matched inspiration effort, which was not the case for PSV.

We also showed that PAV+ increases the risk of delayed cycling, and that effort may be shorter than ventilator T_I in this mode.[5,12] Confirming the findings of previous studies,[5,10] we found that PAV+ resulted in V_T values lower than those obtained with PSV. Lower V_T values can reduce the risk of air trapping and ventilatory overassistance.

The Auto-Trak function applies multiple algorithms derived from flow, volume, and pressure measurements during the respiratory cycle to trigger and cycle the ventilator. The shape signal is one of those algorithms. It is a mech-
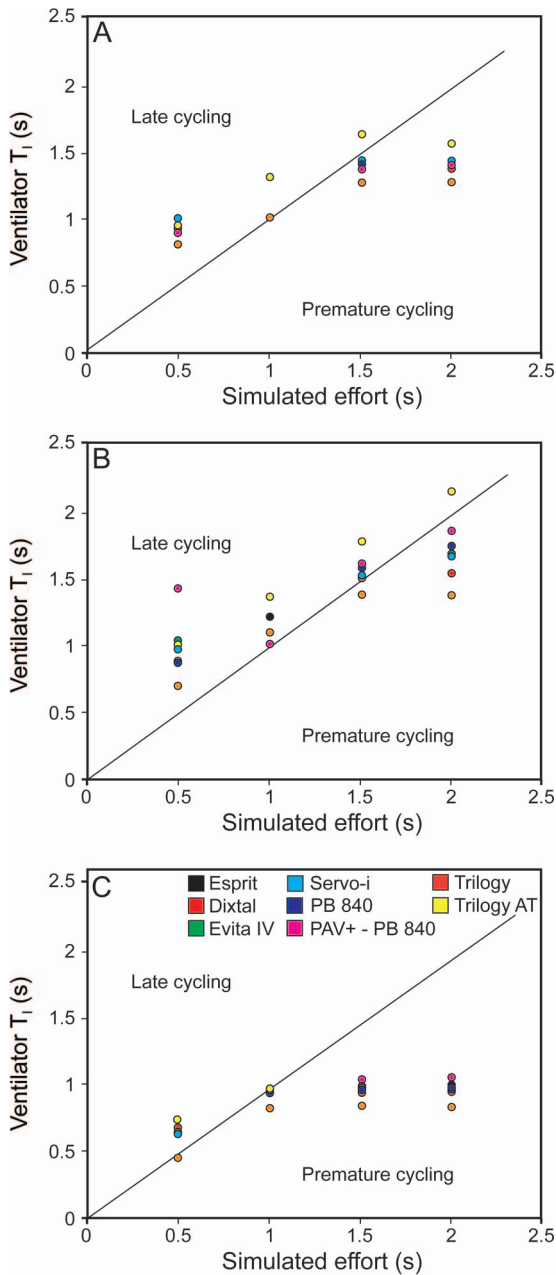
Fig. 3. The correlation between the ventilator inspiratory time (T_I ventilator) and duration of effort in the normal (A), obstructive (B), and restrictive (C) respiratory mechanics profiles. PAV+ = proportional assist ventilation plus, Trilogy AT = Trilogy with Auto-Trak.

Fig. 4. Tidal volume (V_T), according to the duration of effort, in normal (A), obstructive (B), and restrictive (C) respiratory mechanics profiles. Simulation of effort at 1.5 and 2 s in the restrictive profile was not feasible in PAV+ mode because the ventilator failed to activate that mode in the configuration. PSV = pressure support ventilation, PAV+ = proportional assist ventilation plus, Trilogy AT = Trilogy with Auto-Trak.

anism that works for both triggering and cycling of the ventilator. This is a virtual waveform of the real flow curve of the previous cycle, except it is 15 L/min less and 300 ms delayed in relation to the real cycle. When the patient makes a respiratory effort and the real flow curve crosses the virtual signal, inspiratory assistance is automatically triggered. Similarly, when the effort ceases or expiratory effort occurs, the flow waveform changes its slope and intersects with the virtual waveform, and cycling occurs.[23]
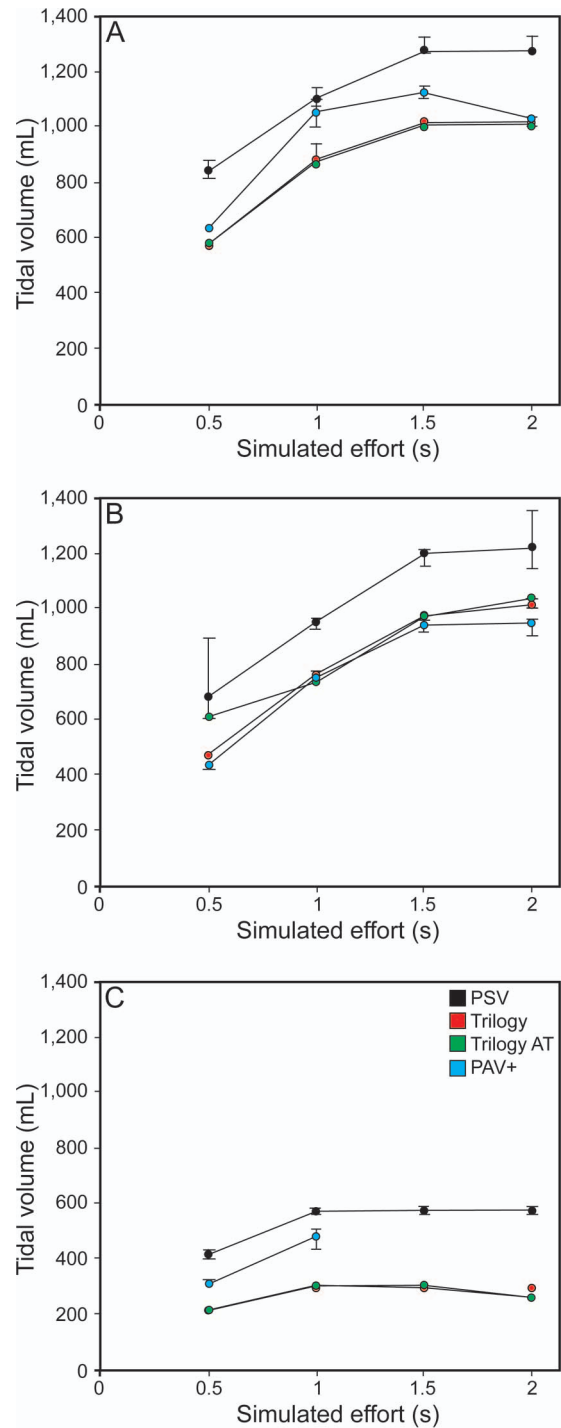
In comparison with PSV with a fixed cycling-off criterion, the virtual waveform has been shown to decrease patient triggering effort and to improve ventilator performance.[30] However, the virtual waveform system can also generate asynchrony. In a previous study conducted by our research group, Auto-Trak and manual adjustments of the cycling-off criteria showed similar results with respect to patient-ventilator synchrony and patient comfort.[23] In the present study, the use of Auto-Trak in a single-limb circuit ventilator showed similar results to conventional settings concerning cycling asynchrony.

Previous studies have shown that an inspiratory trigger delay of <100 ms has negligible clinical effects.[31,32] In the present study, we found that the inspiratory trigger delay was below that threshold for all ventilators when the respiratory mechanics were normal or restrictive, although it was above the threshold when the respiratory mechanics profile was obstructive, the difference being due, in part, to the presence of auto-PEEP. The PAV+ mode significantly reduced inspiratory trigger delay. This is in contrast with previous findings that the triggering function is not influenced by the ventilation mode[12] and might be related to the fact that the lower V_T values in PAV+ mode reduce auto-PEEP. The use of Auto-Trak was also associated with a significant reduction in the inspiratory trigger delay and eliminated auto-triggering asynchrony.

This study has some limitations. We used a mechanical model of the respiratory system, and our results should be confirmed in real patients. Nevertheless, given the difficulties of studying the determinants of patient-ventilator interaction at the bedside, the lung simulator enabled us to conduct such investigations, showing good reproducibility and reliability, as well as to avoid risks for patients in clinical investigations.[33] In addition, the P_{mus} employed varied in duration but not in intensity. Furthermore, we tested only pressure triggering (not flow triggering). Moreover, the pressurization time (rise time function), which is known to influence mechanical ventilation synchrony,[16,33] was not modified in PSV mode. Finally, the experimental setting did not include simulation of cardiogenic oscillations, which could cause auto-triggering.

Our findings have practical implications. Although the results highlight the limitations of the PSV and PAV+ modes in preventing mechanical ventilation asynchrony, PAV+ was superior in that it offered inspiratory support proportional to respiratory muscle effort, thus avoiding premature cycling, excessive V_T values, and overassistance. The Auto-Trak system was also associated with less asynchrony in triggering and cycling, because it automatically adjusts both and simplifies the operation of the ventilator.

Conclusions

Mechanical ventilation asynchrony is influenced by the effort, respiratory mechanics, ventilator type, and ventilation mode. In the PSV mode, delayed cycling was more common with shorter effort in the obstructive respiratory mechanics profile, whereas premature cycling was more common with longer effort and the restrictive profile. The Auto-Trak system with the single-limb circuit ventilator improves triggering function. PAV+ can prevent premature cycling but not delayed cycling, especially in the obstructive respiratory mechanics profile, and is associated with lower V_T values than is PSV. Further clinical investigations are needed to confirm these experimental findings.

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