Work of Breathing in Adaptive Pressure Control Continuous Mandatory Ventilation

Eduardo Mireles-Cabodevila MD and Robert L Chatburn RRT-NPS FAARC

BACKGROUND: Adaptive pressure control is a mode of mechanical ventilation where inflation pressure is adjusted by the ventilator to achieve a target tidal volume (V_T). This means that as patient effort increases, inflation pressure is reduced, which may or may not be clinically appropriate. The purpose of this study was to evaluate the relationship between ventilator work output and patient effort in adaptive pressure control. METHODS: A lung simulator (ASL 5000) was set at compliance = 0.025 L/cm H_2O and resistance = 10 cm H_2O/L/s. Muscle pressure (P_{mus}) was a sine wave (20% inspiration, 5% hold, 20% release) that increased from 0–25 cm H_2O in steps of 5 cm H_2O. The adaptive-pressure-control modes tested were: AutoFlow (Dräger Evita XL), VC+ (Puritan Bennett 840), APV (Hamilton Galileo), and PRVC (Siemens Servo-i and Siemens Servo 300). The target V_T was set at 320 mL (P_{mus} = 15 cm H_2O, inspiratory pressure = 0 cm H_2O) to allow delivery of a realistic V_T as the simulated patient demanded more volume. All measurements were obtained from the simulator. RESULTS: Patient work of breathing (patient WOB) increased from 0 J/L to 1.88 J/L through the step increase in P_{mus}. Target V_T was maintained as long as P_{mus} was below 10 cm H_2O. V_T then increased linearly with increased P_{mus}. The ventilators showed 3 patterns of behavior in response to an increase in P_{mus}: (1) ventilator WOB gradually decreased to 0 J/L as P_{mus} increased; (2) ventilator WOB decreased at the same rate as P_{mus} increased but plateaued at P_{mus} = 10 cm H_2O by delivering a minimum inspiratory pressure level of 6 cm H_2O; (3) ventilator WOB decreased as in patterns 1 and 2 to P_{mus} = 10 cm H_2O, but then decreased at a much slower rate. CONCLUSIONS: Adaptive-pressure-control algorithms differ between ventilators in their response to increasing patient effort. Notably, some ventilators allow the patient to assume all of the WOB, and some provide a minimum level of WOB regardless of patient effort. *Key words: mechanical ventilation, work of breathing, computer control, adaptive-pressure-control ventilation*. [Respir Care 2009;54(11):1467–1472.

Introduction

Adaptive-pressure-control (APC) ventilation consists of an adaptive targeting scheme to adjust the inspiratory pressure to deliver at least the minimum target tidal volume (V_T). APC was introduced with the Servo 300 ventilator (Siemens, Maquet Critical Care, Solna, Sweden) in 1991; now this mode is available on most current critical-care ventilators. APC seems an attractive option, given that the V_T is "targeted" (giving the feeling to the operator of "control") while inspiration is pressure-controlled (increasing flow synchrony). A commonly cited benefit of APC is "automatic weaning," where inspiratory pressure decreases as the respiratory system characteristics improve and patient effort is restored. However, APC cannot distinguish improving lung mechanics from an inappropriate increase

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in patient effort, thus leaving open the possibility of decreasing ventilator support on a patient who needs it. This was clearly illustrated by Jaber et al[1] in patients ventilated with APC. They found that when there is an increase in ventilatory demand (by increasing instrumental dead space), APC inappropriately decreased ventilator support, leading to a resultant increase in patient work of breathing (patient WOB).

In a passive model (no spontaneous breaths), all modes of ventilation are expected to generate the same amount of WOB (ventilator WOB) for a given V_T and respiratory system characteristics (resistance and compliance). However, as patient effort (patient WOB) increases, the behavior of each mode differs.[2] The theoretical behavior of APC is similar to that of volume-control ventilation: as patient effort (patient WOB) increases, the ventilator WOB decreases. In contrast to volume control, in APC the V_T and flow can vary and be larger than the set target.[3]

The characteristics of APC, both positive (increased flow synchrony, "automatic weaning") and negative (uncontrolled maximum V_T, inappropriate decrease in ventilator WOB), have been pointed out in recent reviews, but barely researched.[4,5] Studies have demonstrated, contrary to expected, that APC resulted in higher WOB[1,3] and less patient comfort,[6] when compared with other conventional modes of ventilation. Furthermore, reaching conclusions regarding APC is hampered by its presence in several brands of ventilators, each with different proprietary algorithms and different, if subtle, mechanical breath characteristics.[4] We performed the following study in order to establish what differences, if any, each APC algorithm has and to characterize the response of APC to progressive increase in patient effort.

Methods

We evaluated 5 critical-care ventilators capable of delivering APC modes, with a lung simulator programmed to create a step increase in patient effort. We used previously published values to obtain the respiratory characteristics (resistance and compliance) of patients with acute respiratory distress syndrome (ARDS).[7,8] We used an ARDS model for 2 reasons. First, given the low compliance, P_{mus} generally results in smaller V_T and does not reach the volume limits of the ventilator. Second, the only clinical study on APC and WOB was done in patients with ARDS,[3] so our results would be additive.

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Lung Simulator

A high-fidelity servo lung simulator (ASL 5000, IngMar Medical, Pittsburgh, Pennsylvania) was used to model an active respiratory system composed of a single linear constant resistance and single constant compliance (resistance = 10 cm H_2O/L/s, compliance = 0.025 L/cm H_2O). These variables were kept constant during all the experiments. The simulator was programmed to increase P_{mus} (0, 5, 10, 15, 20, and 25 cm H_2O) every 20 breaths. The maximum P_{mus} was selected based on results from Colebatch et al,[9] reporting 25 cm H_2O as the maximal transpulmonary pressure required to achieve total lung capacity. P_{mus} was modeled with a 25% rise, then a 5% hold and a 25% decrease (arbitrarily chosen to simulate a sine pattern of muscle effort). P_{mus} did not change during mechanical ventilation (no muscle unloading programmed). The lung simulator breath rate was 20 cycles/min. Data from the simulator were recorded in a high-resolution file (500 Hz sampling frequency) and used to measure the ventilator output (volume, flow, and pressure) and WOB. Hereafter, we use patient WOB to refer to the WOB done by the simulator. We obtained total WOB and patient WOB from the simulator software analysis of the Campbell diagram. We then manually calculated the ventilator WOB by subtracting patient WOB from total WOB. This calculation is possible because the patient WOB (ie, due to the preset P_{mus}) remained constant regardless of the ventilator support.

Ventilators

We evaluated 5 mechanical ventilators: Evita XL (Dräger Medical, Lübeck, Germany), 840 (Puritan Bennett/Tyco Healthcare, Mansfield, Massachusetts), Galileo, (Hamilton Medical, Bonaduz, Switzerland), Servo-i (Siemens, Maquet Critical Care, Solna, Sweden), and Servo 300 (Siemens, Maquet Critical Care, Solna, Sweden). The ventilators were connected to the lung simulator using a conventional circuit (70 inches long) with separate inspiratory and expiratory limbs (Airlife, Cardinal Health, McGaw Park, Illinois). The same circuit was used for all the experiments. No humidifier was used. The ventilators were calibrated and tested for leaks prior to the experiments.

Experimental Protocol

To characterize the behavior of APC in low and high patient effort, we first had to determine the relationship between lung-simulator-generated demand and resultant V_T. Hence, we did a test run (step increases in effort, from 5 to 25 cm H_2O, in increments of 5 cm H_2O) disconnected from the mechanical ventilator. The V_T and inspiratory time were obtained for each step effort increase. The V_T

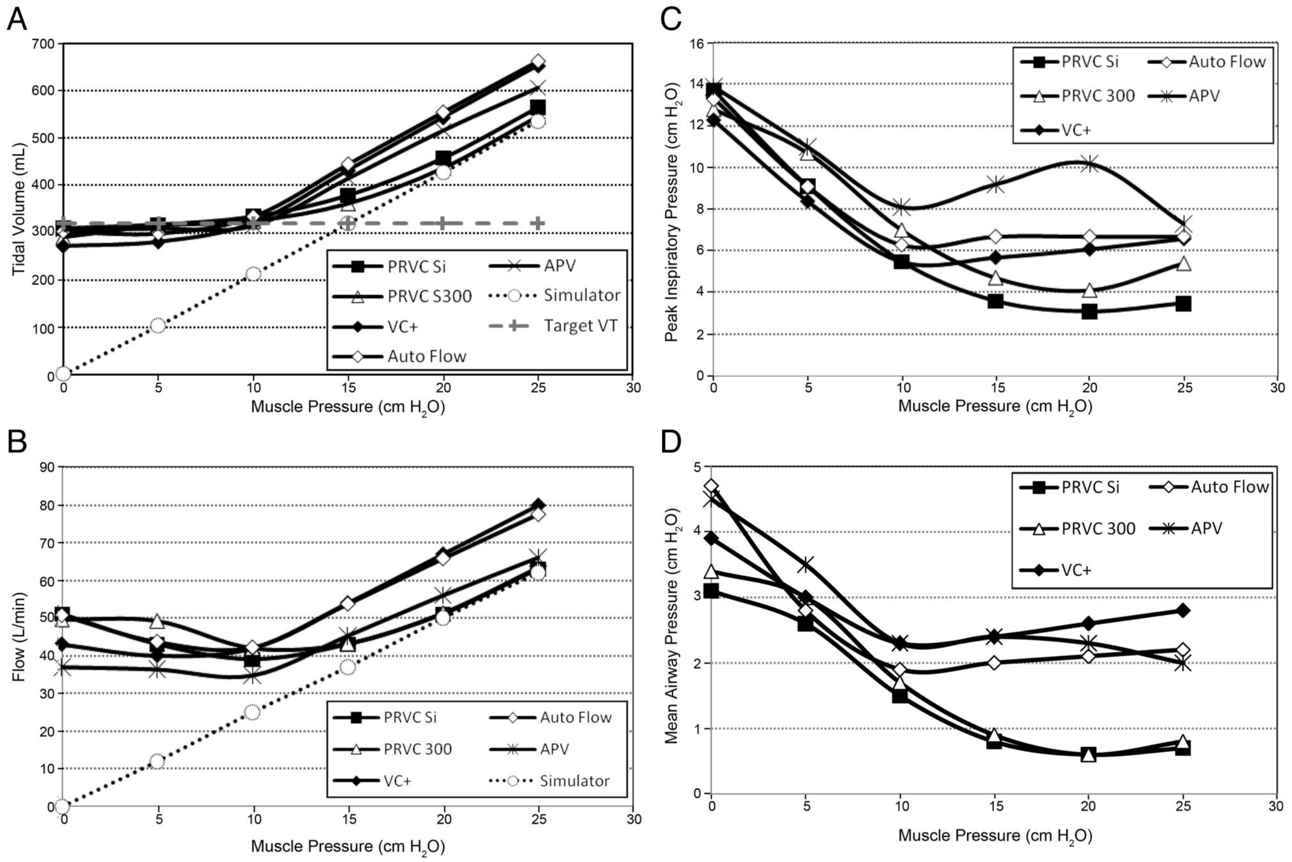

Fig. 1. Ventilation outcomes of adaptive-pressure-control ventilation. PRVC = Pressure-Regulated Volume Control on the Siemens Servo-i (Si) or Siemens Servo 300 (300). VC+ = Volume Control+ on the Puritan Bennett 840. APV = Adaptive Pressure Ventilation on the Dräger Evita XL. V_T = tidal volume.

(320 mL) obtained at a P_{mus} of 15 cm H_2O was used to set the target V_T, since it represented the midpoint between minimal (5 cm H_2O) and maximal simulated patient effort (25 cm H_2O). The inspiratory time (0.83 s) remained constant throughout the effort step increase.

Each ventilator was set in the mode that delivers APC as continuous mandatory breaths (ie, time-triggered and time-cycled inspiration): Dräger AutoFlow; Puritan Bennett 840 Volume Control+; Hamilton Galileo Adaptive Pressure Ventilation (APV); and Siemens Maquet Pressure-Regulated Volume Control (PRVC). The ventilator rate was set at 19 cycles/min, with a flow trigger set at the minimum necessary before causing auto-triggering (to avoid trigger asynchrony and/or trigger work interference). The target V_T and inspiratory time were set as described above. The inspiratory rise time (or similar setting) was set to the minimum possible. All ventilator settings remained the same throughout the simulated run. All experiments were conducted using room air (fraction of inspired oxygen [F_{IO_2}] = 0.21) and reported as measured. No positive end-expiratory pressure was used (to avoid any interference from the exhalation manifold).

Statistical Analysis

Continuous variables were summarized using mean and standard deviation when appropriate. Group comparisons with respect to quantitative variables were descriptive and graphed to represent the mathematical model and ventilator performance. For clarity, we will refer to the simulator findings as patient throughout the text.

Results

The unassisted (simulated) patient WOB went from 0 (no P_{mus}) to 1.88 J/L (P_{mus} = 25 cm H_2O). At 15 cm H_2O, the effort midpoint, for a V_T of 320 mL, the WOB was 1.13 J/L. The 5 ventilators tested generated a ventilator WOB of 1.13 ± 0.4 J/L while delivering the target V_T of 320 mL in passive conditions, thus generating the same WOB as the patient did at the midpoint (Fig. 1A).

The ventilators showed 3 patterns of behavior (Fig. 2) in response to an increase in P_{mus}. For each APC pattern, total WOB is partitioned into its 2 components (Fig. 3A-C): ventilator WOB and patient WOB. The upper border

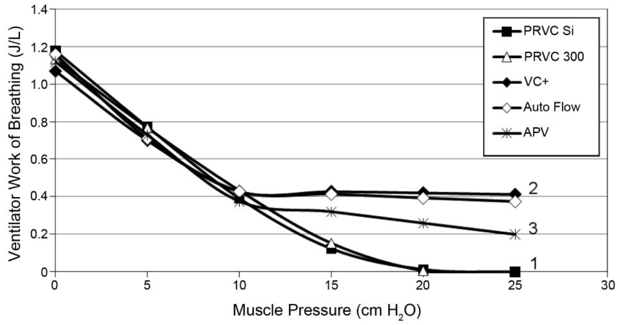

Fig. 2. Work-of-breathing patterns. Ventilator work of breathing versus patient effort (muscle pressure). As patient effort increased, the adaptive-pressure-control algorithms had 3 distinct control patterns. PRVC = Pressure-Regulated Volume Control on the Siemens Servo-i (Si) or Siemens Servo 300 (300). VC+ = Volume Control+ on the Puritan Bennett 840. APV = Adaptive Pressure Ventilation on the Dräger Evita XL.

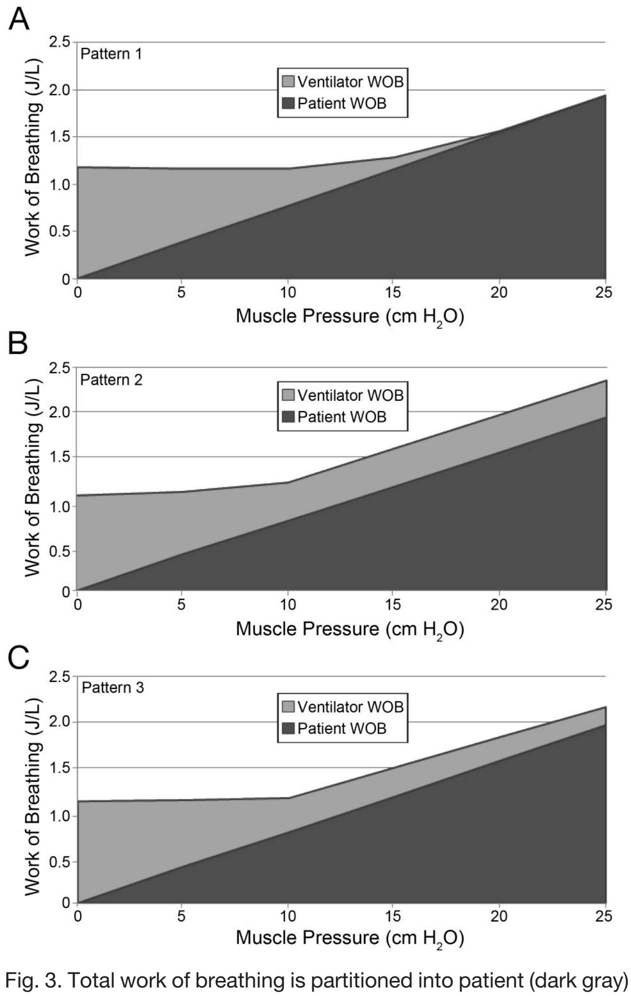

Fig. 3. Total work of breathing is partitioned into patient (dark gray) and ventilator (light gray) work of breathing, according to the 3 patterns observed.

of the graph represents total WOB. Note that total WOB higher than the self-generated patient WOB (patterns 2 and 3) is due to the design of the study; that is, if there was any assistance from the ventilator, it was additive to the patient WOB, not due to increased patient WOB. Furthermore, there was no muscle unloading programmed in this model (ie, P_{mus} modified by airway pressure or patient "backing off" feature on the ASL 5000). Figure 4 shows representative pressure, volume, and flow waveforms for the 3 patterns at different P_{mus} levels.

APC Pattern 1: PRVC. Ventilator WOB gradually decreased to 0 J/L as P_{mus} increased. That is, as patient effort increases and generates V_T equal or above the ventilator set target volume, the ventilator inspiratory pressure is reduced to the minimum necessary to maintain the airway pressure at 0 cm H_2O (see Figs. 1, 2, and 3A).

APC Pattern 2: AutoFlow and VC+. Ventilator WOB decreased at the same rate as P_{mus} increased, but plateaued at P_{mus} = 10 cm H_2O by delivering a minimum inspiratory pressure level of 6 cm H_2O (see Figs. 1, 2, and 3B). That is, as patient effort increases and generates V_T above or equal to the ventilator set target, the ventilator inspiratory pressure is reduced, but never below a minimum set by the ventilator algorithm.

APC Pattern 3: APV. Ventilator WOB decreased as in patterns 1 and 2 to P_{mus} = 10 cm H_2O, but then decreased at a much slower rate (see Figs. 1, 2, and 3C). This pattern seems to be a combination of patterns 1 and 2. There are certain characteristics that make APV behavior harder to characterize. First, the inspiratory rise time in the Hamilton Galileo ventilator is limited to a minimum of 0.50 s. This characteristic alters the pressure waveform (see Fig. 4). Second, as effort increased above the midpoint, the inspiratory pressure rose and then decreased (see Fig. 1C). Lastly, the protocol did not increase effort above 25 cm H_2O to see the ventilator WOB behavior thereafter.

Volume and Flow

All the APC modes delivered V_T slightly below or at the set target until a P_{mus} of 10 cm H_2O was reached (see Fig. 1A). Afterwards, V_T increased according to the APC pattern. In pattern 1, V_T was on average 3% higher than the simulator-generated V_T. In pattern 2, V_T was on average 20%, and in pattern 3 V_T was 23%, higher at 15 cm H_2O, and 12% higher at 25 cm H_2O.

Ventilator-delivered peak flow below the midpoint was 43 ± 5 L/min (see Fig. 1B). At or after the midpoint, difference in flow above the simulator-generated flow was dependent on the inspiratory pressure set by the APC pattern (pattern 2 higher flow than pattern 1).

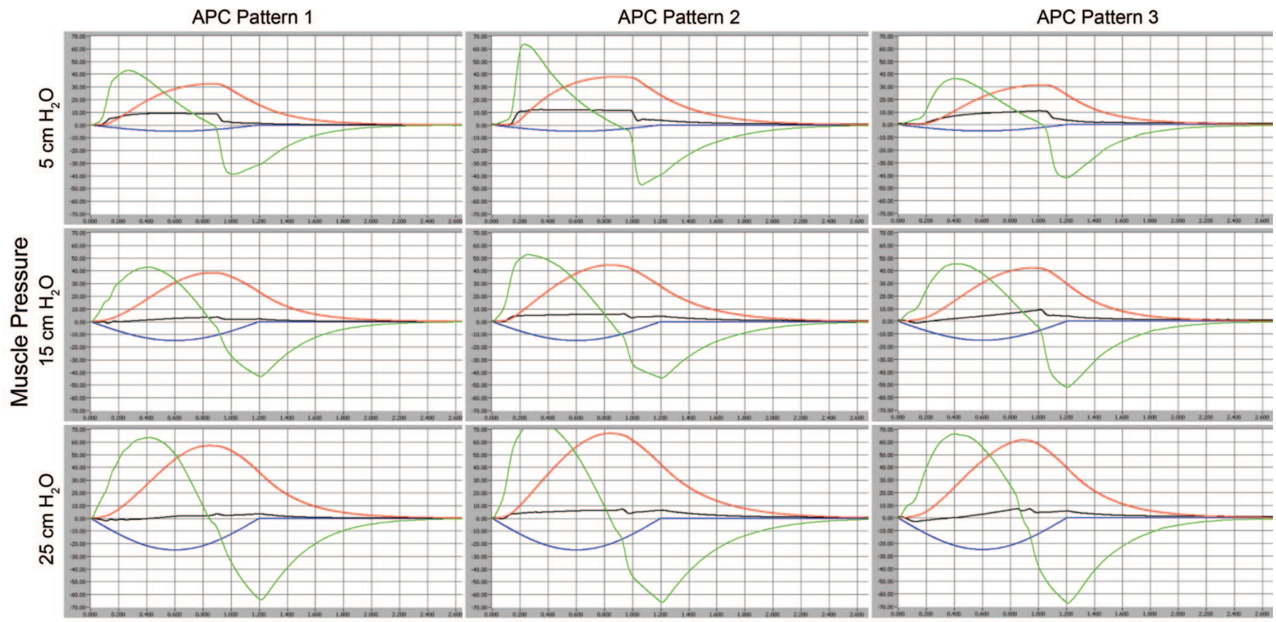

Fig. 4. Representative ventilator waveforms of adaptive pressure control at muscle pressures of 5, 15, and 25 cm H_2O. Blue line = P_{mus}; black = P_{AW}; green = flow; red = volume.

Airway Pressures

All the ventilators kept mean airway pressure above 0 cm H_2O (see Fig. 1D). Peak inspiratory pressure and mean airway pressure behavior for APC patterns 1 and 2 was similar to the WOB pattern. The peak inspiratory pressure in pattern 3 was higher than the other patterns; however, mean airway pressure was similar to pattern 2 (see Fig. 1C).

Discussion

The main findings of this study are: (1) ventilators in the APC mode demonstrate different patterns of ventilator-support decrease as P_{mus} increases, due, presumably to different targeting schemes, and (2) tidal volume delivered in excess of the set target is resultant of patient effort equal to or greater than the pressure needed to generate the set V_T. In other words, when patients attempt to breathe at a V_T greater than the clinician-set target V_T, the burden of inspiratory work is shifted onto the patient as the ventilator attempts to constrain V_T delivery.

Our findings have clinical and research implications. In the clinical area, clinicians caring for patients receiving APC must note that patients who consistently have higher target V_T than set are receiving the minimal amount of support from APC. The interpretation should be either that the ventilator support is not needed (patient is weaned), or the support is inappropriately low. Our study also helps clarify a common misconception regarding variable flow being more comfortable per se. APC uses pressure-controlled inspiration. In pressure control using a set point pressure targeting scheme (ie, inflation pressure is preset by the operator and remains constant), the resultant flow in a passive model will be a smooth, decreasing exponential waveform, and in a spontaneously breathing patient it will be variable to accommodate variations in patient inspiratory effort. However, because of the adaptive pressure targeting scheme employed in APC, the reduction of support associated with increased effort (to keep V_T on target) will paradoxically reduce the flow provided by the ventilator, thus potentially causing the patient discomfort.[10,11] This is further demonstrated in Figure 1B. A patient with low effort will have higher flows delivered by the ventilator (in our model at P_{mus} of 5 cm H_2O, 72% of the flow is ventilator delivered), versus a patient with high effort, where the patient generates most of the flow (at 25 cm H_2O, 18% of the flow is ventilator delivered).

In the research area, studies evaluating WOB and "automatic weaning" in patients on APC need to acknowledge differences between ventilators and breath-delivery algorithms, since outcome differences may depend on the minimum level of support provided. These differences become evident in 2 clinical trials evaluating APC. Betensley et al[6] compared comfort according to the mode of ventilation used: volume control (square flow waveform), pressure support, or APC (PRVC on the Siemens Servo 300, which was the baseline ventilation mode). They used a visual analog scale to evaluate 14 awake and stable adult patients receiving invasive mechanical ventilation. No peak inspiratory pressure was reported for APC, but pressure support was titrated to achieve a V_T of 8 mL/kg. Interestingly, they found that both volume control and pressure support were statistically more comfortable than APC. Although multiple factors (inappropriately set inspiratory time, rise time, inspiratory-expiratory ratio, or the Hawthorne effect) can account for the differences found in this study, it highlights the fact that in this group of patients the design of the study was unfavorable for the patients in APC. That is, the Servo 300 ventilator may have reduced support to 0 cm H_2O, translating into more WOB and discomfort for the patient.

Another example of an APC algorithm affecting results is a trial that evaluated APC and WOB. Kallet et al[3] evaluated 14 patients with ALI/ARDS with previous evidence of asynchrony requiring increase in volume or sedation. They compared WOB between volume control, pressure control, and APC (AutoFlow, Dräger). Attempts were made to set the inflation pressure in pressure-control ventilation to deliver a target $V_T < 8$ mL/kg predicted body weight; however, by protocol, it was never less than 10 cm H_2O inflation pressure. The study demonstrated that WOB and pressure-time product were highest on APC, followed by pressure control, and lastly volume control. When we compared our results with the Kallet et al study we found similarities. The patient spontaneous breathing pattern values were similar to what we chose as the midpoint (us vs Kallet: V_T 5.2 mL/kg vs 4.6 mL/kg [61 kg predicted body weight], peak flow 37 L/min vs 38 L/min, and inspiratory time 0.83 s vs 0.79 s). The compliance was similar too: 25 mL/cm H_2O versus 29 mL/cm H_2O. Not surprisingly, our results on AutoFlow were also similar: total WOB 1.57 J/L versus 1.35 J/L, peak flow 54 L/min versus 57 L/min, and V_T 7.2 ml/kg versus 6.9 mL/kg, and this was at an esophageal pressure of 17 cm H_2O, compared to our P_{mus} of 15 cm H_2O midpoint. These results suggest that the patients were already at or close to the minimal amount of support provided by AutoFlow (6 cm H_2O). If this had been done with another mechanical ventilator, the results may have shown even more increase in WOB.

Conclusions

APC algorithms differ among ventilators in their response to increasing patient effort. Notably, some ventilators allow the patient to assume all of the WOB, and some provide a minimum level of WOB regardless of patient effort. Because APC modes are almost universally available, the clinician and the researcher should be aware of these differences to enhance application and interpretation.

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