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Comparison of the effects of pressure support ventilation delivered by three different ventilators during weaning from mechanical ventilation

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Abstract *Objective:* To compare the effects of pressure support ventilation (PSV) delivered at the same level by three different ventilators on patients' work of breathing (WOB), breathing pattern and gas exchange.
Design: Prospective, self-controlled clinical study.
Setting: Intensive care unit of a tertiary university hospital.
Patients: Nine intubated adult patients during weaning from mechanical ventilation.
Interventions: Patients were randomly connected to one of three ventilators: the Siemens Servo 900 C (SC), the Ohmeda CPU 1 (CPU), and the Engström Erica (EE) during both zero cmH_2O PSV and 15 cmH_2O PSV.
Measurements and results: During zero PSV, there was no significant difference in terms of WOB, V_T, V_E, or auto-PEEP among the three ventilators, although there was a trend towards higher levels of WOB with EE. During 15 cmH_2O PSV, WOB was significantly less with SC than with EE or CPU (0.47 ± 0.48 J/l for SC, 1.0 ± 0.48 for EE and 0.78 ± 0.51 for CPU 1, $p = 0.003$). WOB was 64% less than at zero PSV with SC but only 38% less with EE. This was associated with a different pressurization shape, as assessed by the interior surface of Paw-V_T loops (1.23 ± 0.09 J/l for SC, 0.9 ± 0.02 for EE, and 0.79 ± 0.18 for CPU; $p < 0.001$). At 15 cmH_2O PSV, auto-PEEP was significantly lower with SC than with EE (1.7 ± 2.1 cmH_2O for SC, 4.7 ± 3.6 for EE, and 2.8 ± 0.3 for CPU; $p = 0.04$). External expiratory resistances, in $cmH_2O/l/s$, were significantly higher with EE than with CPU or SC (12.9 ± 3.2 EE, 7.5 ± 2.4 CPU, 5.9 ± 0.5 SC; $p < 0.001$).
Conclusion: During PSV, the different working principles of different mechanical ventilators profoundly affect patient's WOB. Among the various factors, velocity of pressurization of PSV may play a role in its efficacy in unloading the respiratory muscles.

Key words Pressure support ventilation · Respiratory mechanics · Work of breathing · Weaning · Mechanical ventilation

Introduction

Pressure support ventilation (PSV) is an assisted mode of mechanical ventilation in which the patient's inspiratory effort is supported by the delivery of a mechanically driven flow with the aim of maintaining proximal airway pressure at a constant level throughout inspiration. This form of mechanical aid to lung inflation allows the patient to control respiratory rate and timing and, at least partially, flow and tidal volume. It allows a good synchrony between patient and ventilator and is now widely used in clinical practice.

Increasing levels of PSV induce a decrease in transdiaphragmatic pressure and diaphragmatic pressure-time index, while tidal volume increases and respiratory rate decreases [1–3]. In addition, during weaning from mechanical ventilation, a gradual increase in PSV levels leads to a progressive diminution of work of breathing and of the oxygen consumption of the respiratory muscles [2, 3]. If a face mask is used, intubation and mechanical ventilation can be avoided, which is particularly desirable in patients with chronic obstructive pulmonary disease admitted for acute respiratory failure [4]. Finally, it has recently been shown that PSV may shorten the duration of weaning from mechanical ventilation, although the results obtained with PSV seem to be highly dependent on the protocol design [5, 6].

Little is known, however, about the influence of each ventilator's particular algorithm for delivering pressure support, about the effects of changing the velocity of pressurization (i.e. the time to set pressure support level), or about the effects of modifying the expiratory trigger threshold [7, 8]. Although the use of minimum "threshold" levels of pressure have been proposed, precise guidelines for using this technique in the management of patients during weaning from mechanical ventilation are not easily defined, in part due to the differences that exist among mechanical ventilators. We wondered whether, all other factors being equal, the type of mechanical ventilators used could influence breathing pattern, work of breathing or gas exchange in patients recovering from acute respiratory failure during weaning from mechanical ventilation.

Materials and methods

Patients

Nine adult patients in the phase of weaning from mechanical ventilation were studied prospectively. Five were women and four, men; their mean age was 67 years (range: 55–77 years). The patients' relevant clinical data are shown in Table 1.

All patients were orotracheally or nasotracheally intubated. Eligibility criteria for the study included clinical stability and steady hemodynamic conditions, coupled with inability to sustain prolonged (>1 h) periods of spontaneous breathing without demonstrating clinical signs of respiratory distress.

All patients were monitored by ECG, and all but one had an indwelling arterial cannula, allowing to monitoring of blood pressure and for blood sampling for arterial gas analysis. All were studied in a semirecumbent position. Informed consent was obtained from all patients or the next of kin. The protocol had been approved by the ethics committee for research of our institution.

Table 1 Clinical characteristics of the patients (*CRF* chronic renal failure; *COPD* chronic obstructive pulmonary disease)

Patient	Sex/age	FiO_2	Etiology of respiratory failure
1	M/55	0.50	CRF, after cardiac surgery
2	F/65	0.35	Post cardiac surgery
3	F/52	0.40	COPD
4	F/67	0.50	Congestive heart failure
5	F/75	0.55	Ischemic heart disease
6	M/77	0.60	Bacterial meningitis
7	M/77	0.40	COPD
8	F/63	0.40	Stroke
9	M/72	0.40	Coma

Protocol

Patients were evaluated while breathing with three different ventilators: CPU-1 (Ohmeda; Maurepas, France), Erica (Engström, Bromma, Sweden), and Servo 900 C (Siemens, Solna, Sweden). Each ventilator was tested with two set-ups: zero cmH_2O PSV (0 PSV) and fifteen cmH_2O PSV (15 PSV). No external positive end-expiratory pressure (PEEP) was added in any patient. This design permitted the comparison of the effort required to open the demand valve and overcome the resistance of circuits and expiratory valves (during 0 PSV) among the ventilators, and to compare the effects of delivering PSV with different working principles (during 15 PSV). Changes in respiratory mechanics, breathing pattern and arterial blood gases attributable to the use of PSV (changes from 0 to 15 PSV) could also be assessed.

Trigger sensitivity was set at its minimum level in each ventilator and was unchanged throughout the study. All studies were performed using the same external equipment and the same standard corrugated disposable plastic tubings in the external respiratory circuit. A heat and moisture exchanger was used to provide inspired gas conditioning. Briefly, the characteristics of the ventilators are as follows: the Servo 900 C (SC) is pressure triggered to inspiration and flow cycled to exhalation and when flow decreases to 25% of peak, pressure support is terminated [9]. CPU-1 (CPU) and Erica (EE) both have an inspiratory flow trigger [10, 11]; this is non-adjustable in CPU (it is set at about 2 l/min) and adjustable in EE. In both CPU and EE, exhalation is flow cycled when inspiratory flow falls below 6 l/min [10, 11]. Additionally, SC rises rapidly to preset pressure (in about 200 ms), whereas CPU and EE reach preset pressure more slowly (in >300 ms) according to data obtained in a bench study [12, 13]. The time delay between initiation of inspiratory effort and onset of inspiratory flow is less than 200 ms for all three ventilators at the minimum level of trigger sensitivity [12–14]. Due to specific system characteristics of SC and CPU, there is a slight increase in Paw above the atmospheric level (of no more than 2 or 3 cmH_2O) at the very end of inspiration during zero PSV [15].

The three different ventilators were randomly assigned to the patients. Subsequently, the order in which the two different modes (0 PSV and 15 PSV) were employed was also randomized. Volume assist-control mechanical ventilation was resumed between periods of PSV until heart rate, arterial blood pressure and respiratory rate returned to basal level. FiO_2 was maintained unchanged throughout the study. Each test period lasted approximately 30 min.

Measurements

Airflow was measured with a heated Fleisch #2 pneumotachograph (Metabo; Epalinges, Switzerland) connected to a differential pressure transducer (Validyne MP 45±2.5 cmH_2O; Validyne Engineering Corp.; Northridge, Calif., USA). The pneumotachograph was placed between the ventilator Y-piece and the endotracheal tube. Tidal volume (V_T) was obtained from integration of flow signal.

Airway pressure (Paw) was measured at the airway opening by means of a differential pressure transducer (Validyne MP 45±50 cmH_2O). Esophageal pressure (Peso) was measured with a thin latex esophageal balloon filled with 0.5 ml of air and connected to a differential pressure transducer (EMA A.C.G. 1000, ±70 cmH_2O; Plaisir, France) by means of a polyethylene tube. The esophageal catheter was introduced through a nostril after previous topical anesthesia, and its correct placement was validated according to the occlusion test [16].

Analog unfiltered signals of airflow, Paw, and Peso were digitized at 32 Hz and acquired with an Apple IIe microcomputer for subsequent data analysis. Pressure and flow signals were also recorded on separate channels of a strip chart recorder (Gould Brush 260; Gould Instruments, Cleveland, Ohio, USA). From the airflow signal were automatically computed V_T, respiratory rate (RR), minute ventilation (V_E), inspiratory duty cycle (Ti/Ttot), and the mean inspiratory flow (V_T/Ti).

The inspiratory work of breathing (WOB) performed by the respiratory muscles (WOBeso) was measured as the area enclosed within plots of Peso and inspiratory V_T and the static elastic recoil pressure of the chest wall, as previously described [2, 17]. During 15 PSV, we also computed the area enclosed within plots of Paw and inspiratory V_T to assess the efficacy of the ventilators' pressurization [18, 19]. Indeed, when patients are actively pulling on the ventilator during PSV, the Paw-V_T area (WOBaw) depends on the degree of adaptation of the ventilator to the patients' demands. Values of WOBeso and WOBaw in joules (J), are expressed as power of breathing (J/min) or as work per liter of ventilation (J/l).

All values of WOBeso were corrected for auto-PEEP levels when present. We calculated dynamic auto-PEEP [20, 21] from the beginning of the negative deflection in Peso tracing occurring near the end of expiration (which represents the onset of the inspiratory effort) to the first point corresponding to zero airflow [2, 17, 22].

In the last 5 min of each period, data were recorded for subsequent analysis. Calculation of WOBeso, WOBaw and breathing pattern included the averaged values of at least ten consecutive respiratory cycles. During 15 PSV, we calculated from the Paw and flow tracings the expiratory resistance (Rexp) of the different ventilators by measuring Paw for an expiratory airflow rate of 0.5 l/s. Arterial blood was collected in heparinized plastic syringes, and these samples were immediately analyzed for arterial pH and blood gases with an ABL 30 apparatus (Radiometer, Copenhagen, Denmark). Heart rate and arterial blood pressure were continuously monitored and displayed on an oscilloscope.

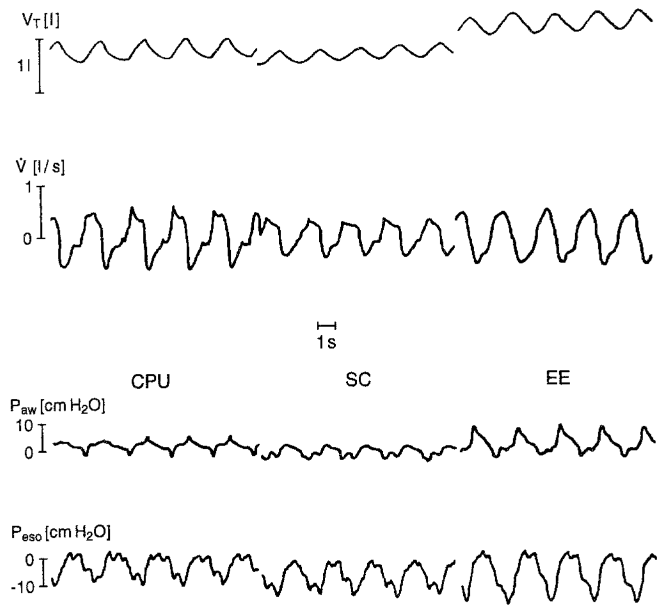

Fig. 1 Tracings of tidal volume (V_T), airflow ($\dot{V}$), airway pressure (*Paw*) and esophageal pressure (*Peso*) obtained during zero cmH_2O PSV with the different ventilators: CPU-1 (*CPU*), Servo 900 C (*SC*) and Engström Erica (*EE*). There is almost no pressurization during inspiration, although there is an increase in Paw during expiration, especially with EE, indicating a high expiratory circuit resistance with this ventilator

Statistical analysis

All data are expressed as mean values±SD. Data were analyzed by means of a two-way analysis of variance. When the *F*-value showed a significant difference, then a Tukey's test was used to detect differences among groups. *p*-values < 0.05 were considered to be statistically significant.

Results

Zero PSV (breathing without pressure support)

Data concerning WOB, breathing pattern and auto-PEEP during this period of spontaneous breathing via the ventilator circuit are shown in Table 2. Figure 1 shows

Table 2 WOB and breathing pattern during 0 PSV ($n = 9$); mean ± SD

	CPU	EE	SC	*p*-value
WOBeso (J/min)	13.1±6.3	14.6±6.6	11.3±6	0.1
WOBeso (J/l)	1.42±0.48	1.62±0.60	1.31±0.69	0.1
V_T (ml)	345±87	332±78	332±69	0.6
RR (breaths·min^{-1})	27.5±7.5	27.7±7.2	26.2±6	0.3
V_E (l/min)	9.08±1.98	8.87±1.65	8.56±2.04	0.3
Ti/Ttot (%)	42.4±4.8[a]	40.2±2.7[b]	42.4±5.1	0.02
V_T/Ti (ml/s)	357±30	368±60	338±60	0.08
Auto-PEEP (cmH_2O)	3.4±1.5	5.1±2.7	3.6±2.7	0.1

[a] Statistically significant difference between CPU and EE
[b] Statistically significant difference between EE and SC

Table 3 WOB and breathing pattern during 15 PSV ($n = 9$); mean ± SD

	CPU	EE	SC	p-value
WOBeso (J/min)	7.4 ± 5.1	9.7 ± 6.0[b]	4.5 ± 5.1	0.01
WOBeso (J/l)	0.78 ± 0.51	1.0 ± 0.48[b]	0.47 ± 0.48[c]	0.03
WOBaw (J/l)	0.79 ± 0.18	0.90 ± 0.024[b]	1.23 ± 0.09[c]	0.0003
V_T (ml)	403 ± 66	399 ± 63	427 ± 81	0.2
RR (Breaths min^{-1})	23.5 ± 6.6	23.7 ± 6.9	21.8 ± 5.7	0.4
V_E (l/min)	9.21 ± 1.62	9.22 ± 2.01	9.04 ± 1.29	0.8
Ti/Ttot (%)	44.3 ± 6.9[a]	39.7 ± 4.5	37.1 ± 5.1[c]	0.008
V_TTi (ml/s)	349 ± 30	390 ± 60	418 ± 90[c]	0.03
Auto-PEEP (cmH_2O)	2.8 ± 0.3	4.7 ± 3.6[b]	1.7 ± 2.1	0.04

[a] Statistically significant difference between CPU and EE
[b] Statistically significant difference between EE and SC
[c] Statistically significant difference between SC and CPU

representative tracings of tidal volume, airflow, airway pressure and esophageal pressure obtained with the different ventilators. The WOBeso, expressed as power or as J/l, tended to be lower with the SC ventilator, although the differences were not statistically significant. Figure 2 shows power of breathing during zero PSV.

Breathing pattern tended to be rapid and shallow, without differences among ventilators. Ti/Ttot was significantly shorter during EE than during CPU or SC study periods ($p = 0.02$). Values of auto-PEEP and V_T/Ti did not show significant differences among ventilators. Peak Paw, expressed in cmH_2O, did not differ among ventilators, being 2.8 ± 0.8 for SC, 2.3 ± 0.7 for EE, and 3 ± 1 for CPU ($p = 0.2$).

Arterial blood gas analysis showed that PaO_2 ranged between 122 ± 39 mmHg and 132 ± 39 mmHg ($p = 0.3$), for a mean FiO_2 of 0.45. $PaCO_2$ was significantly higher ($p = 0.01$) during breathing with EE (48 ± 10 mmHg) and SC (47 ± 13 mmHg) than with CPU (43 ± 8 mmHg). There was no significant change in heart rate (HR) or arterial blood pressure (ABP) among the different periods: HR was 94 ± 18 beats/min for all ventilators, systolic ABP ranged from 137 ± 27 to 142 ± 27 mmHg, and diastolic ABP ranged from 73 ± 18 to 83 ± 12 mmHg.

Fifteen PSV (pressure-supported breathing)

Data concerning WOB, breathing pattern and auto-PEEP during this period are shown in Table 3. Figures 3 and 4 show representative tracings (at two different speeds) of airflow, airway pressure and esophageal pressure obtained with each ventilator. WOBeso, expressed as power or as J/l, decreased to a significantly lower value with SC than with the other ventilators ($p < 0.01$). Figure 5 shows power of breathing during 15 PSV. Values of WOBaw also showed significant differences between SC and the other two ventilators ($p < 0.001$), reflecting a better adaptation

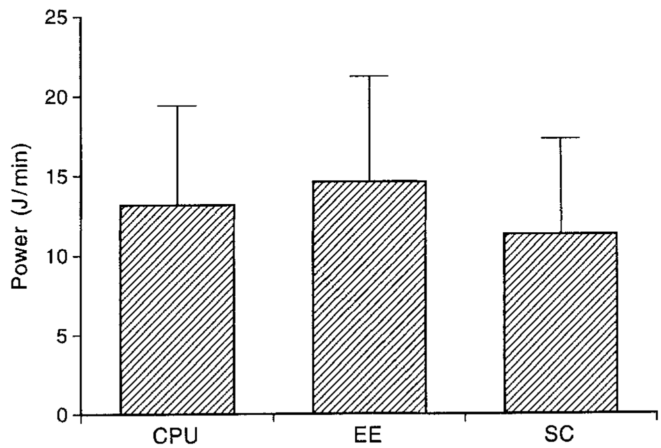

Fig. 2 Mean values of WOB (±SD) expressed as power (J/min) obtained with the different ventilators used, Servo 900 C (*SC*), CPU-1 (*CPU*), and Engström Erica (*EE*), during zero cmH_2O PSV. No statistically significant differences were found among the ventilators

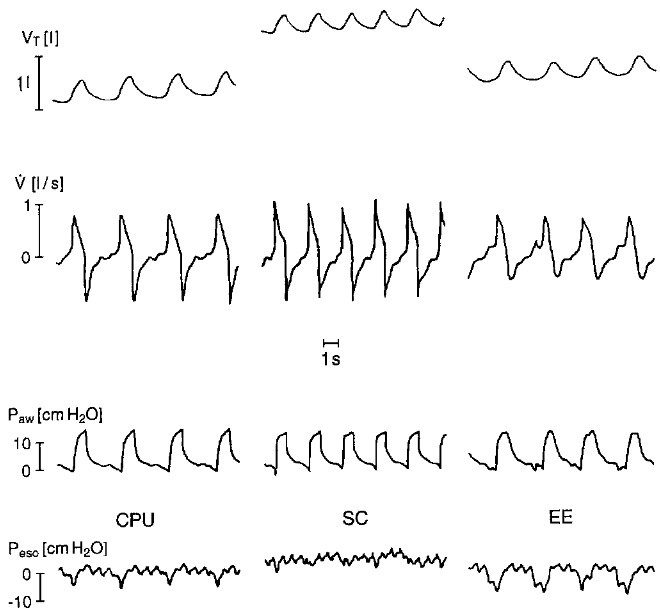

Fig. 3 Tracings of tidal volume (V_T), airflow ($\dot{V}$), airway pressure (*Paw*) and esophageal pressure (*Peso*) obtained during 15 cmH_2O PSV with the different ventilators: CPU-1 (*CPU*), Servo 900 C (*SC*) and Engström Erica (*EE*). For identical ventilator settings, the V_T is similar, but the esophageal pressure swings differ among the ventilators, thereby indicating different values of work of breathing

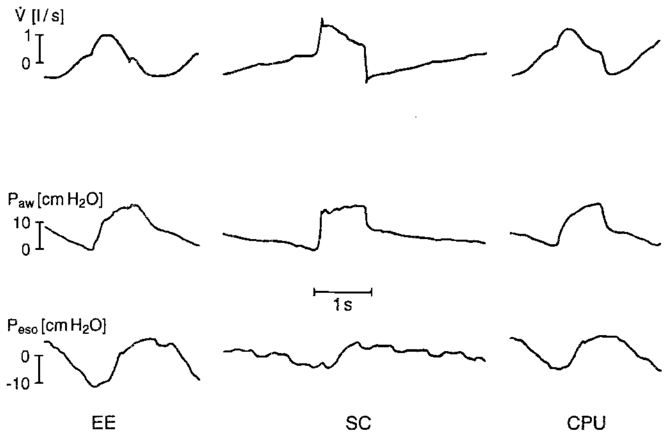

Fig. 4 Representative tracings of airflow ($\dot{V}$), airway pressure (*Paw*) and esophageal pressure (*Peso*) recorded during one breathing cycle with 15 cmH_2O PSV, with the Servo 900 C (*SC*), the CPU-1 (*CPU*), and the Engström Erica (*EE*). Note the different characteristics of the ventilators: pressure triggering, rapid rise in airflow, maintenance of a near constant plateau pressure and cycling about 25% of peak flow with SC; flow triggering, slow rise in airflow, achievement of preset pressure near the end of inspiration and cycling near zero flow with both EE and CPU. Note also the high expiratory resistance (slow expiratory decay of Paw) during ventilation with EE

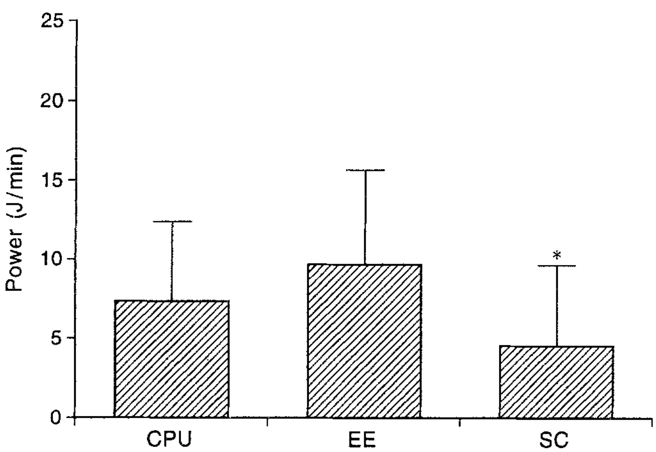

Fig. 5 Mean values of WOB (±SD) expressed as power (J/min) obtained with the different ventilators used, Servo 900 C (*SC*), CPU-1 (*CPU*), and Engström Erica (*EE*), during 15 cmH_2O PSV. The *asterisk* denotes a statistically significant difference between SC and the other ventilators ($p < 0.01$)

of SC to the ventilatory demands of these patients. Peak Paw expressed in cmH_2O was similar among ventilators: 14.3±0.7 for SC, 14.5±1 for EE, and 14±1.5 for CPU ($p = 0.6$).

Values of V_T and V_E were not significantly different among the ventilators. Ti/Ttot was significantly higher during CPU than during EE or SC ($p = 0.008$), and V_T/Ti was higher during SC and EE than during CPU ($p = 0.03$). Patients exhibited significantly lower levels of auto-PEEP during breathing with SC than with EE ($p = 0.04$). R_{exp} at a flow of 0.5 l/s and expressed in cmH_2O/l/s was significantly higher ($p < 0.001$) during EE (12.9±3.2) than during CPU (7.5±2.4) or SC (5.9±0.5).

Arterial blood gases did not differ among the ventilators: PaO_2 ranged from 127±42 to 145±48 mmHg ($p = 0.06$), and $PaCO_2$ ranged from 43±8 to 44±9 mmHg ($p = 0.4$). HR ranged from 91±18 to 92±21 beats/min, systolic ABP ranged between 131±27 and 134±27 mmHg, and diastolic ABP ranged between 74±15 and 77±12 mmHg, with no statistically significant differences among the ventilators.

Comparison between zero PSV and fifteen PSV

Values of WOBeso during zero PSV, expressed either in J/min or in J/l, were significantly higher than during 15 PSV. The maximum decrease in power and in WOB/l was observed with SC (60 and 64%, $p < 0.01$) and the minimum, with the EE (33 and 38%, $p < 0.001$); the values for CPU were intermediate (43 and 45%, $p < 0.03$).

During 15 PSV, V_T was significantly increased compared to 0 PSV: by 16% with CPU, by 20% with EE, and by 28% with SC ($p < 0.01$ in all cases). In addition, RR dropped significantly from 0 to 15 PSV: by 14% with CPU and EE and by 16% with SC ($p < 0.03$ in all cases). V_E did not change significantly between 0 and 15 PSV.

Breathing with 15 PSV did not change Ti/Ttot compared with 0 PSV, although it tended to be shorter with SC (37% vs 42%, respectively), $p = 0.052$. V_T/Ti was significantly higher during 15 PSV than during 0 PSV with EE ($p = 0.03$) or SC ($p = 0.01$), but not CPU ($p = 0.6$).

Between 0 and 15 PSV, PaO_2 did not change, and $PaCO_2$ decreased significantly ($p < 0.05$) only with EE and SC. Finally, there were no significant changes in either HR or ABP between 0 and 15 PSV.

Discussion

Our study shows that the different working principles, by which PSV is delivered, significantly influence the WOB dissipated by the respiratory muscles. Below we discuss the most relevant findings during 0 and 15 PSV.

The values of WOBeso during 0 PSV did not differ among the three ventilators. However, these values tended to be higher with EE than with SC or CPU. This could result from a low level of pressurization applied by the ventilators, even at a nominal setting of 0 PSV. No difference in the WOBeso was reported when SC and the earliest version of CPU 1 were compared during spontaneous breathing in patients without pressure support, despite significant differences in WOBaw [19]. This suggests that the demand valves, respiratory circuits and different triggering mechanisms (pressure or flow) of the ventilators studied had only a minor influence on the work dissipated by the inspiratory muscles, at least in this group of patients and under the conditions of this study. This is in line with the absence of changes observed in breathing pattern among the SC, EE and CPU. The auto-PEEP values measured in our study during 0 PSV are similar to those reported in previous investigations [2, 19, 23].

As expected, pressure-supported breathing with 15 PSV significantly decreased the WOBeso in comparison with 0 PSV [1, 2]. This reduction in WOBeso differed in magnitude among the ventilators. During 15 PSV, the lowest levels of WOBeso were measured during breathing with SC. This difference was not associated with significant differences in V_T, RR or V_E among the three ventilators. The measurements of inspiratory WOB that we performed are valid if several assumptions are taken into account. First, the theoretical value of chest wall compliance should correspond to its real value. Indeed, an abdominal or thoracic surgical procedure may induce alterations in chest wall compliance. However, even in the case of abnormal chest wall compliance, a similar error would account for all periods without major influence on the results, since breathing pattern did not differ substantially among the ventilators. Second, major work due to distortion of the chest wall is not assessed by these measurements. A major influence of distortion is unlikely, however, except during vigorous inspiratory efforts. Another limiting factor could be related to the absence of steady state after 30 min, when measurements were done. To partially obviate this problem, all patients began the different study periods at the same basal state (volume assist-control ventilation), and all data were collected in the last 5 min of a 30-min period.

The apparent superiority of one ventilator over the others (here, that of SC over CPU or EE) may be explained by several factors. The SC delivers a fast and high flow rate at the beginning of inspiration, thus allowing for a rapid pressurization. This particular type of flow profile may be put forward as optimal for patients with high respiratory loads and strong respiratory drive [7, 15]. In a preliminary report, we also found lower transdiaphragmatic pressure and lower airway occlusion pressure when studying patients in the process of weaning from mechanical ventilation with a fast rather than a slow initial airflow rate during pressure support breathing [7]. The mechanism by which a rapid velocity of pressurization decreases WOBeso may be related to better matching of the patient's flow demand by the ventilator. Indeed, a slow progressive rise in pressure may result in delayed delivery of assistance to the patient [24, 25]. It is possible that, in our study, the slow velocity of pressurization of EE and CPU exposed patients to breathe with excessive effort, thus causing them to develop a higher WOBeso. The significantly higher WOBaw found with SC indicates that the ventilator action resulted in a higher pressurization of the circuit and that the flow delivered by this ventilator best matched the flow delivery needs of the patients. In fact, WOBaw is the result of the ventilator's pushing and the patients pulling of gas, thus reflecting the amount of work done by the ventilator to inflate the respiratory system of the patient.

In addition, Ti/Ttot was shorter with SC than with CPU, which may be explained by the design of this ventilator. With SC, pressure support is terminated when inspiratory flow reaches 25% of its peak value, whereas EE and CPU have a flow cycling from inspiration to expiration when airflow is close to zero. The shorter Ti/Ttot found during 15 PSV with SC may, then, facilitate expiration because of a longer expiratory time. Additionally, the significantly lower expiratory resistances measured during 15 PSV with SC in comparison to EE may facilitate pulmonary emptying and thus decrease dynamic hyperinflation. Moreover, an increase in the expiratory resistances may enhance dyspnea and increase the inspiratory work of breathing [26]. All of these findings, together with a slightly lower RR and V_E, may also explain the lower values of auto-PEEP and may contribute to the lower WOBeso measured during 15 PSV with SC. Although the patients we studied were heterogeneous and had a wide range of clinical diagnoses, all of them shared the characteristic of being difficult to wean.

In summary, during mechanical assistance with PSV, different methods of delivering the pressure wave may profoundly affect patients' work of breathing. The results of the present study suggest that several factors may influence the efficacy of PSV, possibly including demand-valve sensivity and expiratory valve resistance, and that a rapid velocity of pressurization may be preferred to better unload the respiratory muscles.

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