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Original Article

Evaluation of Pressure Support Ventilation with Seven Different Ventilators Using Active Servo Lung 5000

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In modern emergency and critical care, physicians tend to choose the mode of mechanical ventilation based on spontaneous breathing for the purpose of promoting discharge of pulmonary secretion and preventing atelectasis in patients with acute respiratory insufficiency. However, we often observe "differences in recovery" among patients treated using the same PSV settings beyond "differences in individual characteristics." We evaluated the Pressure Support Ventilation (PSV) mode aiming to certify the difference among 7 representative mechanical ventilators using the Active Servo Lung 5000 (ASL 5000) respiratory simulation system. The following parameters were measured: The time delay that resulted in the lowest inspiratory pressure from the point at which the ventilator recognized spontaneous breathing (TD), the lowest inspiratory airway pressure (cmH_2O) generated prior to the initiation of PSV (ΔPaw), the work of breathing while triggering required to achieve the lowest inspiratory negative pressure from the beginning of inspiratory support (WOBtrig), and the inspiratory work of breathing (WOBi). The mean TD of the Puritan-Bennett type 840 (PB840) was significantly shorter than those of other ventilators ($p < 0.01$). The WOBtrig of the PB840 was significantly lower than those of others ($p < 0.01$). However, the WOBi values of the Servo-I and T-Bird were greater than the others, with the Evita series showing the smallest WOBi of the 7 ventilators tested. According to this simulation study using ASL 5000, we concluded that PB840 was the most rapid response ventilator, but the Evita series was the gentlest mechanical ventilator among 7 ventilators from the standpoint of the total work of breathing during the inspiration phase in the setting of PSV.

Key words: work of breathing, pressure support ventilation, mechanical ventilation, active servo lung (ASL5000).

Most newly released ventilators provide continuous positive airway pressure (CPAP) ventilation or pressure support ventilation (PSV) modes in order to restore and support the patient's spontaneous breathing. Many of these ventilators intended to treat acute respiratory insufficiency are described as being "gentle to the patient." Manufacturers advertise that their products are gentle to patients because of their excellent triggering function on inspiration and high sensitivity to spontaneous breathing. PSV has been

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shown to decrease patients' work of breathing (WOB), especially during the weaning process. Mancebo *et al.* reported that WOB during inspiration was between 38–64% less with the addition of 15 cmH_2O of PSV, using 3 different ventilators in nine intubated adults who were being weaned from ventilator support in an intensive care unit [1]. We also often use PSV for weaning ventilated patients. However, we occasionally observe different weaning speeds in the recovery phase among patients treated with the same PSV settings, beyond "no differences in individual settings" among each ventilators. These differences in recovering may be due to the individual condition. Each ventilator made by a different manufacturer should have a different mechanism of supporting the patients. Richard *et al.* reported a benchmark test study in which the performance levels of 22 ventilators, set in PSV mode, were tested under different conditions [2]. They reported that with regard to PSV and trigger performance, the new generation ventilators as well as some piston and turbine-based ventilators outperformed most previous-generation ventilators. It is useful to have information based on comparative benchmark test results before using each mechanical ventilator, as it is impossible to compare several ventilators in the same clinical situation. The purpose of this study was to evaluate 7 recently released ventilators made by 5 different manufacturers for treating acute respiratory insufficiency in terms of PSV mode with a focus on the early phase of inspiration using the ASL 5000 simulation system (Fig. 1, 2).

Materials and Methods

Active Servo Lung 5000. The Active Servo Lung 5000 (ASL 5000) is a simulator of every patients' respiration. It works on the basis of patients' simulation data programmed by exclusive application (Fig. 1). Lung parameters, R (Resistance) and C (Compliance), are simulated by appropriate piston movement in response to pressure changes. This movement is digitally controlled without the use of springs or orifices to achieve the utmost precision and versatility. The ASL 5000 system includes 3 software packages from simulation to analysis. The ASL 5000's software is based on LabVIEW™, National Instrument's versatile instrumentation software <http://www.ni.com/labview/>. This provides a graphical interface and the capacity to easily integrate other sources of data.

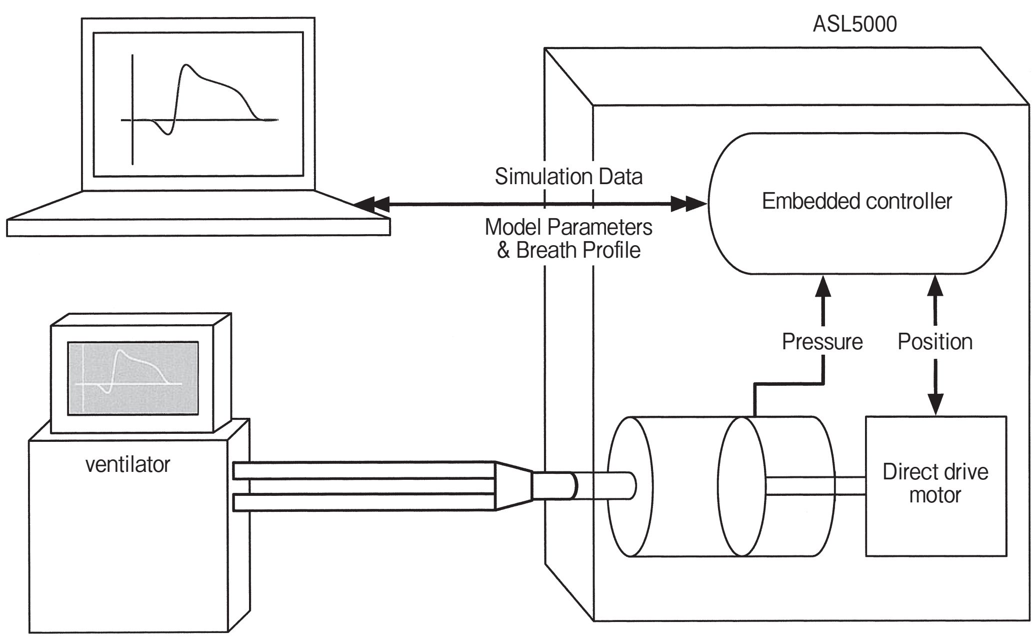

Fig. 1 Schematic explanation of Active Servo Lung 5000 (ASL 5000), a lung simulation system used for the analysis of mechanical ventilators.

The following 7 ventilators were evaluated:

Puritan-Bennett type 840 (PB840; Nellcor Puritan-Bennett, Pleasanton CA, USA), Servo-i (MAQUET Critical Care AB, Sweden), Evita 4 and XL (Dräger Medical, Lübeck, Germany), Esprit (Respironics Inc., Pittsburgh, USA), and VELA and T Bird (VIASYS Healthcare Inc. Conshohocken, PA, USA).

The basic settings for each ventilator were as follows:

The bias flow of each ventilator was set at the default value for adults (PB840: base flow 2 L/min fixed, Servo-i: bias flow 2 L/min fixed, Evita series: none, Esprit: bias flow 5 L/min fixed, VELA: bias flow 10 L/min(10–20 L/min controllable), T-Bird: bias flow 10 L/min (10–20 L/min controllable)), FIO_2 0.21, Flow trigger 3 L/min(Servo-I; Flow trigger "1"), PEEP 5 cmH_2O, and PSV 15 cmH_2O. The peak flow and pressure-slope each of ventilator were set to the maximum supplied points. Each ventilator was connected to ASL5000 via a standard respiratory disposable circuit (DAR Breathing System, Tyco Healthcare Japan, Tokyo, Japan).

The simulation system ASL 5000 was set as follows:

Uncompensated residual capacity: 300 mL, peak inspiratory pressure: −10 cmH_2O, airway resistance: 10 cmH_2O/L/sec, pulmonary compliance: 20 ml/cmH_2O, single lung mode, spontaneous breathing: 12 bpm, body temperature in the lung: 37 degrees Celsius. The mode of inspiration was set at a half sinusoid curve. The detailed settings for single spontaneous breathing were as follows: inspiratory time: 20%, inspiratory holding time: 2%, inspiratory releasing time: 5%.

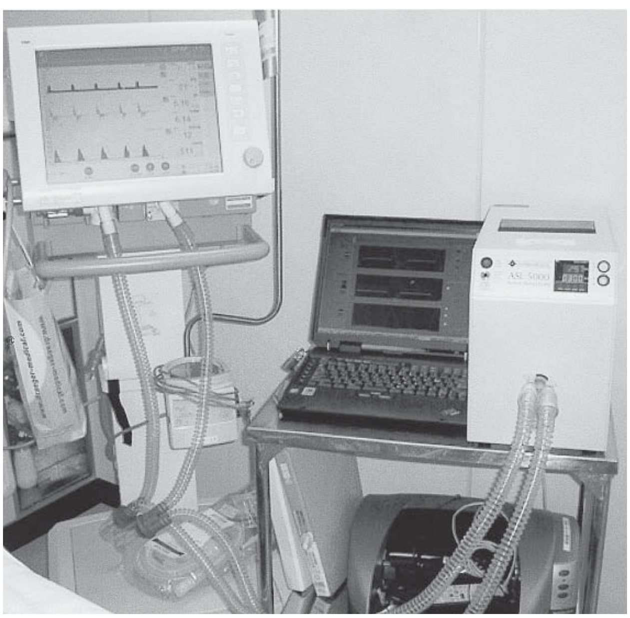

Fig. 2 The actual evaluation test.

Measurements. To assess the efficiency of the ventilator supporting the spontaneous breathing, the airway pressure-time tracing curve was analyzed (Fig. 3). At the initiation of each spontaneous breath, the activated airway pressure drops below the PEEP level. When the inspiratory flow velocity reaches the trigger flow level, the trigger sensing point, the PSV mechanism is activated, and the airway pressure is pushed back to the PEEP level from the lowest inspiratory pressure point. The inspiration is then further supported to reach as high as the preset peak inspiratory pressure (PIP) level. The following parameters were calculated.

1. **TD** (msec): The time delay required to achieve the lowest inspiratory pressure from the point when the ASL 5000 recognized the spontaneous breath.
2. **ΔPaw** (cmH_2O): The lowest inspiratory airway pressure generated after the initiation of PSV.
3. **WOBtrig** (mJ/breath): The work of breathing while triggering required to achieve the lowest inspiratory negative pressure from the beginning of inspiration.
4. **WOBi** (J/L): Patient's inspiratory work of breathing.

The patient's inspiratory work of breathing (WOB, Joule) was measured. WOB is calculated by integrating the pressure applied to the chest wall with respect to the tidal volume from the start of inspiration to the end of inspiration. WOB is transcribed using the following numerical expression:

∫-dPchest wall dV from [Start Inspiration] to [End of Hold].

All parameters were automatically calculated according to the ASL 5000's analyzing software.

Because the tidal volume for each inspiratory cycle is different in pressure support ventilation, we adopted the work of breathing per liter of tidal volume as the parameter to be evaluated. Twenty spontaneous breaths were performed by the simulator, and 10 acceptable data without mechanical error were used for the analysis.

The statistical analysis. The analysis software attached to the ASL 5000 was used. The values are given in Table 1. The statistical analyses were performed by one-factor ANOVA and a post-hoc test (Scheffe's F test). The analysis environment was Microsoft Excel 2004 for Macintosh®, Statcel 2® (Microsoft Excel Plug-in, OMS Publication Co.)

Results

The typical airway pressure-time tracing curve for each ventilator is shown in Fig. 3. The numerical data are shown in Table 1.

The mean TD in PB840 was 91.8 ± 8.28 msec, which was significantly smaller than those of other ventilators ($p < 0.01$).

The ΔPaw of PB840 was significantly smaller than those of the other ventilators ($p < 0.01$). Those for the Servo-I and Evita series were significantly greater than the others ($p < 0.01$). However, there were no differences between Evita series, nor between Servo-I and Evita XL.

The WOBtrig of PB840 was significantly lower in the other ventilators ($p < 0.01$). The WOBtrig of Servo-I was significantly lower than that of Evita 4 ($p < 0.01$). There was no significant difference between

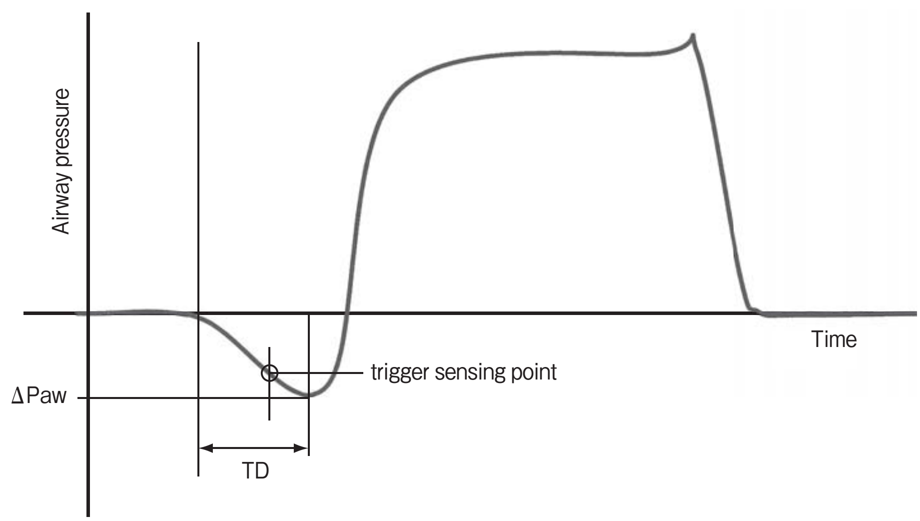

Fig. 3 Schema of the airway pressure-time curve during the inspiratory phase, and parameters. TD, time delay; ΔPaw, lowest inspiratory airway.

Table 1

	PB840	Servo-I	Evita 4	Evita XL	Esprit	VELA	T-Bird
TD, msec	91.8 ± 8.28[a]	136.9 ± 2.88	113.6 ± 8.73	113.6 ± 4.43	125.7 ± 3.27	128.6 ± 7.99	142.1 ± 5.59
ΔPaw, cmH_2O	0.498 ± 0.023[b]	1.294 ± 0.029[c]	1.240 ± 0.131[c]	1.271 ± 0.067[c]	0.903 ± 0.039	0.712 ± 0.038	1.044 ± 0.056
WOBtrig, mj/breath	0.112 ± 0.024[d]	0.715 ± 0.018[e, f]	0.805 ± 0.040[f]	0.772 ± 0.031[f]	0.413 ± 0.028	0.216 ± 0.080	0.507 ± 0.064
WOBi, J/L	0.537 ± 0.002	0.584 ± 0.003[g]	0.520 ± 0.005[h]	0.518 ± 0.003[h]	0.530 ± 0.001	0.552 ± 0.003	0.577 ± 0.006[g]

n = 10.
PB840, Puritan-Bennett type 840; ΔPaw, lowest inspiratory airway; TD, time delay; WOBi, patient inspiratory work of breathing; WOBtrig, work of breathing while triggering.
All values are expressed as means ± SD.
a, $p < 0.01$ shorter vs. all other ventilators; b, $p < 0.01$ smaller vs. all other ventilators; c, $p < 0.01$ greater vs. the other 4 ventilators; d, $p < 0.01$ lower vs. all other ventilators; e, $p < 0.01$ lower vs. Evita 4; f, these 3 ventilators were significantly greater ($p < 0.01$) than the other 4 ventilators; g, *$p < 0.01$ higher than the other 5 ventilators; h, $p < 0.01$ lower than the other 5 ventilators.

Evita 4 and Evita XL. There was no difference between Servo-I and Evita XL. The WOBtrig values of these 3 ventilators were significantly greater than those of the other 4 ventilators ($p < 0.01$). According to the results of TD, ΔPaw and WOBtrig, PB840 responds more quickly to synchronize the spontaneous inspiration, resulting in a reduction of triggering effort in comparison with the other ventilators. The WOBi values of each of the ventilators showed statistical differences. Servo-I and T-Bird required a greater WOBi than the other 5 ventilators ($p < 0.01$), and the WOBi of the Evita series was significantly smaller than those of the other ventilators ($p < 0.01$). Based on the WOBi results, the total consumption of energy required for each inspiration by the patient is lowest in the Evita series.

Discussion

This study, performed on an ASL 5000, involved the comparison of 7 different ventilators under a limited state of simulated clinical conditions. Because this evaluation would not have been possible in clinical patients, a model lung simulation test was used to compare a number of ventilators. The ASL5000 is very useful device for evaluating different ventilators on the "same patient."

Recently, new ventilators used in acute intensive care have been commonly released for clinical use after being checked in a standardized evaluation (*e.g.*, draft reviewer guidance of ventilators by CDRH of FDA, USA). For example, in the USA, the ECRI Institute suggested to various medical institutions how they could select the best matching ventilator using Failure Mode and Effect Analysis.

But in a clinical situation, each ventilator is routinely used by individuals who are unfamiliar with the comparative evaluation. A large number of experimental and clinical studies designed to test trigger sensitivity have focused on comparisons among different acute and intensive care ventilator systems. In this study, we evaluated the inspiratory performance of 7 recently released commercially available ventilators used for acute intensive care using the same PSV component. The useful feature of this simulation study is that it makes it possible to evaluate and compare any available ventilators under the same simulated clinical conditions.

CPAP systems have been compared on different ventilators [3–7].

On the other hand, though PSV represents a widely used mode of partial ventilatory support during acute respiratory failure and the weaning process, there are few reports that compare different ventilators.

PSV is a partial ventilatory support during which substantial inspiratory muscle activity may remain. Richard *et al.* evaluated 7 ventilators with different PSV components with flow-triggering mode, and concluded that PSV mode reduced the work load for the patients [2, 8]. The trigger mode based on flow detection rather than pressure detection has been implemented in recent ventilators used for acute and intensive care [9, 10]. According to the clinical study by Aslanian et a*l*. WOBi in PSV was 14 ± 12% less with the flow triggering mechanism compared with the pressure triggering mechanism [8]. Sasson *et al.*

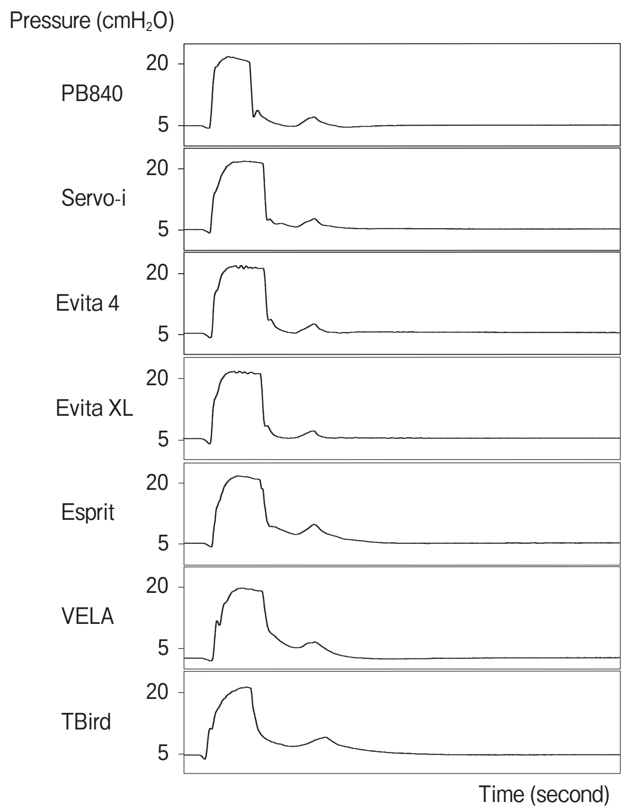

Fig. 4 Actual drawing of one typical wave form during the inspiratory phase in 7 ventilators. PB840: Puritan-Bennett type 840.

found that these ventilators have been claimed to improve patient-ventilator synchrony by reducing triggering effort [11, 12]. In a lung model study using similar methodology, Aslanian *et al.* confirmed the previous findings [2, 8-10] and showed that the breathing effort evaluated in a benchmark test was significantly less with flow triggering than with pressure triggering during PSV in 2 ventilators used for acute and intensive care [1]. Williams *et al.* reported that a smaller WOBtrig as determined by TD and inspiratory trigger pressure (similar to our ΔPaw) led to good triggering of PSV [13].

In this study, it was assumed that if a shorter TD and smaller ΔPaw and WOBtrig were used, less work was required of the patients for inspiration .

This is a so-called "rapid response ventilator," and the patients on this ventilator can breathe more naturally. Though we set up all ventilator-parameters related to PSV ventilation as evenly as possible, the default setting of constant flow is different in each ventilator. This default setting was determined by the individual concept of the manufacturer in order to achieve the most favorable performance for the devices. Therefore, the default setting of each ventilator was used for this study. The ventilator with a constant flow mechanism keeps either the expiratory or the inspiratory valves open.

As a result, the time delay between opening the inspiratory valve and sensing the inspiration was longer than the time delay between sensing the inspiration and the start of the true inspiration effort. Also, ΔPaw is smaller in a device with a constant flow mechanism compared with a non-constant flow device.

The flow trigger of each ventilator was set to 3 L/min. In Servo-I, it was expressed in terms of the simple numbers 1-10, not in "L/min." Users need to select the trigger setting according to the clinical response of the patients, as no actual number for intra-circuit flow rate is shown. In this study, the flow trigger of the Servo-I was set to "1." This setting is the maximum trigger level (100% of 2 L/min base flow) of the Servo-I. Our experiments suggest that this flow trigger setting of Servo-I is nearly compatible with the Evita series in spite of their "different" flow trigger settings.

According to our experiments, PB840 resulted in the most rapid response ventilator of the 7. As the Evita series has no constant flow system, it might have resulted in a longer TD, and greater ΔPaw and WOBtrig compared with those of PB840.

On the other hand, the WOBi of the Evita series was less than those of the other ventilators, although the Evita series may not be a rapid response ventilator in the setting of PSV.

In other words, the Evita series is not good at reducing trigger effort, but may be good at increasing pressure support afterwards, resulting in a reduced total consumption of energy during the inspiration phase in the setting of PSV compared with that of PB840.

T-Bird, a turbine-based ventilator, shows a greater WOBi than the other ventilators except the Servo-I. Richard *et al.* reported that regarding PSV and trigger performance, some new generation turbine-based ventilators outperform most of the previous generation of ventilators [2]. They considered that this result showed that the newer technologies used by manufacturers, *i.e.*, microprocessors, servo-valves, and fast and potent turbines, have substantially improved recent generation ventilators in terms of their global trigger response.

Our results are similar to theirs regarding trigger performance, but the reduction of WOBi in our results went beyond that seen in any other ventilators. The WOBi of Servo-I was greater than in any other ventilators. The reason for this finding is unknown. It may be caused by differences of peak flow or tidal volume between each ventilator. Because this is a mere conjecture, we will research this further in future investigations.

Although there were significant differences among some ventilators in the measurement of WOBi, these are small differences relative to the total work of inspiration. Also, mil Joule is used for the expression of WOBtrig, which is a minute measure compared with the Joules per liter of WOBi. However, it is natural that breathing continues at all times, and mechanical ventilation usually continues for days or weeks, so these small differences would affect the total energy expenditure for patients on ventilators. The users should recognize that there would be a large difference in energy expenditure during the whole course of PSV, even though the ventilator settings are the same and the differences for each breath may be small but significant.

In this experiment, we focused on the early phase of inspiration in respiration.

As we know, one respiration is constituted by inspiration and expiration, so it will be necessary to evaluate the whole WOB of patients, including the inspiratory and expiratory phases, in future investigations.

Summary. According to this simulation study using ASL 5000, we concluded that PB840 was the most rapid response ventilator, but the Evita series was the gentlest ventilator from the standpoint of the total work of breathing during the inspiration phase in the setting of PSV.

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