Performance Characteristics of Five New Anesthesia Ventilators and Four Intensive Care Ventilators in Pressure-support Mode

A Comparative Bench Study

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Background: During the past few years, many manufacturers have introduced new modes of ventilation in anesthesia ventilators, especially partial-pressure modalities. The current bench test study was designed to compare triggering and pressurization of five new anesthesia ventilators with four intensive care unit ventilators.

Methods: Ventilators were connected to a two-compartment lung model. One compartment was driven by an intensive care unit ventilator to mimic “patient” inspiratory effort, whereas the other was connected to the tested ventilator. The settings of ventilators were positive end-expiratory pressures of 0 and 5 cm H2O, and pressure-support ventilation levels of 10, 15, and 20 cm H2O with normal and high “patient” inspiratory effort. Pressure-support ventilation (PSV) is used in the intensive care setting to improve patient–ventilator synchrony and facilitate weaning.6–9

Results: For the five tested anesthesia ventilators, the pressure-support ventilation modality functioned correctly. For inspiratory triggering, the three most recent anesthesia machines (Fabius, Drägerwerk AG, Lübeck, Germany; Primus, Drägerwerk AG; and Avance, GE-Datex-Ohmeda, Munich, Germany) had a triggering delay of less than 100 ms, which is considered clinically satisfactory and is comparable to intensive care unit machines. The use of positive end-expiratory pressure modified the quality of delivered pressure support for two anesthesia ventilators (Kion, Siemens AG, Munich, Germany; and Felix, Taema, Antony, France). Three of the five anesthesia ventilators exhibited pressure-support ventilation performance characteristics comparable to those of the intensive care unit machines. Increasing fresh gas flow (1 to 10 l/min) in the internal circuit did not influence the pressure-support ventilation performance of the anesthesia ventilators.

Conclusion: Regarding trigger sensitivity and the system’s ability to meet inspiratory flow during pressure-supported breaths, the most recent anesthesia ventilators have comparable performances of recent-generation intensive care unit ventilators.

The new-generation anesthesia ventilators tend to be more innovative and sophisticated than their predecessors to allow a better adaptation of the machines to patients’ ventilatory needs. During the past few years, many manufacturers have introduced new modes of ventilation in anesthesia ventilators, especially partial-pressure modalities.1–5

Pressure-support ventilation (PSV) is a ventilatory mode in which the patient’s spontaneous inspiratory effort triggers the ventilator to provide a variable flow of gas that increases until airway pressure reaches a selected level. Thus, during each spontaneous inspiration, the patient receives pressure-limited assisted ventilation. PSV is used in the intensive care setting to improve patient–ventilator synchrony and facilitate weaning.6–9

A few studies have suggested that the use of PSV during general anesthesia could provide some advantages (reduction of atelectasis, improved gas exchange, decreased level of sedation).6,10–13 More often, the use of PSV in the operating room was performed in anesthetized patients with a laryngeal mask airway. Therefore, PSV use progressively increased in the operating room, because spontaneous breathing alone or with ventilatory assistance is recommended with laryngeal mask airway because of leaks.14 Moreover, studies reported that PSV improves gas exchange and reduces work of breathing in anesthetized adults and children with an endotracheal tube 6,12 or laryngeal mask airway.11,13

Several lung model studies, however, demonstrated that technical differences among intensive care unit (ICU),4,15–17 transport,18,19 and home ventilators17,20 may markedly affect their performance, especially regarding the trigger function and the pressurization process. Overall, these studies showed that considerable progress has been made in the performance and functionality of these devices. However, although today...
there are numerous anesthesia ventilators available providing PSV with a standard anesthesia circle system, no studies have evaluated their technical performance. The aim of the current study was to evaluate in a bench study the performance of the new generation of anesthesia ventilators for delivering PSV and to assess how they compare with ICU ventilators.

**Materials and Methods**

**Ventilators Tested**

The five anesthesia ventilators evaluated were the Felix (Taema, Antony, France), Kion (Siemens AG, Munich, Germany), Fabius (Dräger AG, Lübeck, Germany), Primus (Drägerwerk AG), and Avance workstation (GE-Datex-Ohmeda, Munchen, Germany) equipped with the model 7900 ventilator. This last ventilator can also be found in the GE-Datex-Ohmeda Aestiva, Aisys, and Aespire anesthesia workstations. The four ICU ventilators tested were the Servo 900C (Siemens), Servo 300 (Siemens), Horus (Taema), and Evita 4 (Drägerwerk AG). The main characteristics of anesthesia and ICU ventilators tested are presented in table 1.

The machines were provided by the manufacturers after a full revision had been made just before our investigation. All machines were stock, no modification was performed, and all were tested in operating conditions conforming to the manufacturer’s specifications.

**Test Lung Model**

All ventilators were connected to a classic, validated two-compartment lung model (Pneu View AI 2601I TTL; Michigan Instruments, Grand Rapids, MI) which has been described in detail in previous studies.\(^\text{17,20}\) Briefly, the model consists of two separate chambers linked by a rigid metal strip. One chamber is connected to an ICU ventilator (Evita 4; Drägerwerk AG), which is set in volume control mode to mimic patient inspiratory effort (fig. 1). The magnitude and duration of the latter can thus be adjusted by changing the settings on this “driving” ventilator. The two chambers being linked, inflation of the first necessarily inflates the second, which is connected to the ventilator being tested. The onset of passive inflation is therefore detected as an “inspiratory” effort by the tested device, which triggers a pressure-support response. The elastance (E) and airway resistance (R) of each compartment can be adjusted separately.

Thus, the model allows simulation of various magnitudes of inspiratory effort, types of respiratory mechan-
ics, and tested ventilator settings. The ventilator circuits connected to each chamber were equipped with a pneumotachograph and pressure transducer (Biopac Systems, Goleta, CA). Data were acquired online via an analog–digital converter (MP100; Biopac Systems), sampled at 500 Hz, and stored in a laptop computer for subsequent analysis (Acqknowledge software; Biopac Systems).

All measurements were performed in ambient temperature and pressure-saturated conditions. Automatic body temperature and pressure-saturated compensation was disabled on the Evita 4, and all other devices were calibrated in ambient temperature and pressure-saturated conditions. Gas compressibility was not accounted for, given its negligible quantitative contribution in the conditions of the current tests.21

**Measured Variables**

Inspiratory trigger and pressurization ramp were evaluated as previously reported.16,17,20 Figure 2 shows the method used to calculate the trigger characteristics and the pressurization phase during PSV based on the airway pressure–time curve.

**Inspiratory Trigger.** At each sensitivity condition tested, triggering performance was assessed according to three criteria: the time delay, the pressure fall, and the airway pressure–time product per cycle.

- Triggering delay (DT): time between the onset of inspiratory effort and that of detectable pressurization.
- Pressure fall (DP): the maximal decrease in airway pressure measured from its baseline value. DP reflects in such way the inspiratory work required to trigger the ventilator; therefore, the lower its value, the smaller the work required of inspiratory muscles.22
- Airway pressure–time product per cycle (PTP, cm H2O × ms) during the trigger phase, defined as the area under the Paw signal during the DT interval (computed as DP × DT).

**Pressurization.** The pressure–time products at 300 and 500 ms for each respiratory cycle (PTP300 and PTP500) are computed as the area under the time–pressure curve 300 and 500 ms after the onset of inspiratory effort. These two parameters reflect the speed of pressurization and the device’s capacity to maintain the set pressure during inspiratory effort. They depend both on the ventilator’s performance and the magnitude of inspiratory effort, the former being determined by the pressurization ramp and the flow generated by the device’s bellows or piston. PTP300 and PTP500 are expressed in cm H2O · s.

**Experimental Protocol**

DT, DP, PTP, PTP300, and PTP500 were measured as described above and in figure 2 at three successive levels of PSV: 10, 15, and 20 cm H2O.

To mimic normal and strong inspiratory efforts by patients, the tidal volumes of the driving ventilator were set at 220 and 440 ml, respectively. These efforts were actually associated with pressures 100 ms after occlusion (P0.1) of 2 cm H2O (normal effort) and 4 cm H2O (strong effort), respectively, as measured on the bench.16,19 The duration of inspiratory effort on the driving ventilator was set at 1 s for all tests. Inspiratory trigger was set at the maximum sensitivity without the presence of autotriggering. The pressurization slope was set to its steepest value. When the inspiratory:expiratory cycling criteria was adjustable, it was maintained at its default value.

During the tests, E and R of the “driving” chamber were set to normal (E = 20 cm H2O · 1−1, R = 5.6 cm H2O · 1−1 · s).

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Fig. 1. Schematic representation of the experimental setup.

Fig. 2. Schematic drawing of the assessment of the performance of the ventilator triggering systems. DP (cm H2O) and DT (ms) are the changes in pressure and time delay, respectively, required to open the inspiratory valve. PTP is the pressure–time product, expressed as DP × DT (cm H2O × ms). The triggering systems were adjusted to their maximal sensitivity. PEEP = positive end-expiratory pressure.

PTP300 and PTP500 are computed as the area under the pressure curve 300 and 500 ms after the onset of inspiratory effort. These two parameters reflect the speed of pressurization and the device’s capacity to maintain the set pressure during inspiratory effort. They depend both on the ventilator’s performance and the magnitude of inspiratory effort, the former being determined by the pressurization ramp and the flow generated by the device’s bellows or piston. PTP300 and PTP500 are expressed in cm H2O · s.
For all ICU and anesthesia ventilators, the measurements were performed at positive end-expiratory pressure (PEEP) of 0 and 5 cm H$_2$O for each of the two different efforts (normal and strong) and for the three PSV levels (10, 15, and 20 cm H$_2$O).

For the five anesthesia ventilators, two levels of fresh gas flow were tested: 1 and 10 l/min. Thus, 12 conditions were evaluated for each ICU ventilator and 24 conditions were tested for each anesthesia ventilator.

**Statistical Analysis**

All parameter values represent the average of three to five breaths obtained during steady state. All results are expressed as mean ± SD or median with 95% confidence interval, depending on the normal or nonnormal distribution of the variables. Comparative statistics relied on the Kruskal-Wallis one-way analysis of variance on ranks. Post hoc analysis was performed with the Scheffé test if analysis of variance reached significance. Significance was set at $P < 0.05$. 

Fig. 3. Performance of the triggering systems, assessed by pressure drop (DP), trigger delay (DT), and pressure–time product (PTP) of the five anesthesia ventilators and the four intensive care unit ventilators assessed with a normal level of inspiratory effort (P$_0.1$ = 2 cm H$_2$O) with positive end-expiratory pressure = 0 (ZEEP; Z) and positive end-expiratory pressure = 5 cm H$_2$O (PEEP; P) for the three pressure-support ventilation (PSV) levels: 10, 15, and 20 cm H$_2$O. * $P < 0.05$ comparisons between machines. # $P < 0.05$ comparisons between ZEEP and PEEP.
Results

One hundred sixty-eight conditions were evaluated, 120 for the anesthesia ventilators and 48 for the ICU ventilators. None of the ventilators mistriggered, nor did any ventilator prematurely cycle to expiration.

Specific Triggering System Evaluation

DT, DP, and PTP values measured in zero end-expiratory pressure (ZEEP) and with PEEP for all studied ventilators at a level of inspiratory effort (P0.1 = 4 cm H2O) with positive end-expiratory pressure = 0 (ZEEP; Z) and positive end-expiratory pressure = 5 cm H2O (PEEP; P) for the three pressure-support ventilation (PSV) levels: 10, 15, and 20 cm H2O. *P < 0.05 comparisons between machines. # P < 0.05 comparisons between ZEEP and PEEP.

Fig. 4. Performance of the triggering systems, assessed by pressure drop (DP), trigger delay (DT), and pressure–time product (PTP) of the five anesthesia ventilators and the four intensive care unit ventilators assessed with a high level of inspiratory effort (P0.1 = 4 cm H2O) with positive end-expiratory pressure = 0 (ZEEP; Z) and positive end-expiratory pressure = 5 cm H2O (PEEP; P) for the three pressure-support ventilation (PSV) levels: 10, 15, and 20 cm H2O. *P < 0.05 comparisons between machines. # P < 0.05 comparisons between ZEEP and PEEP.
For all machines, DT was not affected by the magnitude of inspiratory effort, except for the Kion, whose TD significantly increased with PEEP (figs. 3 and 4) as inspiratory effort increased.

For all anesthesia ventilators tested, increased fresh gas flow from 1 to 10 l/min did not significantly modify triggering performance on ZEEP or PEEP.

Dynamic Evaluation of PSV

PTP 300 and PTP 500 values measured on both ZEEP and PEEP for all studied ventilators according to a level of P0.1 = 2 cm H2O (normal effort) are presented in figure 5 and to a level of P0.1 = 4 cm H2O (strong effort) are presented in figure 6.

At all levels of PSV studied (10, 15, and 20 cm H2O), the pressurization capacity of all ICU ventilators was comparable, whereas it varied among the anesthesia ventilators, the difference being more marked with PEEP. At 300 ms in PEEP, the values obtained with the Felix and the Kion were half those obtained with the Fabius, Primus, and Avance.

For all ICU ventilators except the Servo 900, PTP 500 was not affected by the magnitude of inspiratory effort. However, with the anesthesia ventilators, PTP 500 tended to decrease as inspiratory effort increased (figs. 5 and 6).

Discussion

The current study is the first to provide a strictly protocoled bench test evaluation of the performance in delivering pressure support of five new-generation anesthesia ventilators. The major findings of this trial can be summarized as follows: (1) For the five tested anesthesia ventilators, the PSV modality functions correctly; (2) performance was more homogeneous among the modern ICU ventilators than among the anesthesia ventilators; (3) the use of PEEP modified the quality of delivered pressure support in two anesthesia ventilators (Kion and Felix) but not in the three others (Fabius, Primus, and Avance); and (4) increasing fresh gas flow (1 to 10 l/min) in the internal circuit did not influence the PSV performance of the anesthesia ventilators.

This bench test study also showed that triggering delay is less than 100 ms for all ICU ventilators except in the older Servo 900C as reported by previous studies15–17,19 and is less than 100 ms only for only two anesthesia ventilators (Primus and Avance); and (4) increasing fresh gas flow (1 to 10 l/min) in the internal circuit did not influence the PSV performance of the anesthesia ventilators.

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The inspiratory workload required to trigger the ventilators (i.e., PTP) is very low for the modern ICU ventilators, in line with previous studies of these machines.17,20 The most recently developed anesthesia
ventilators exhibited comparable performance, the highest PTP being measured in the Kion, which is the first anesthesia ventilator with PSV mode and the oldest of the anesthesia ventilators tested. The best characteristics of the pressurization phase for the anesthesia ventilators were obtained with the Fabius, Primus, and Avance under all tested conditions and were comparable with those of obtained with the ICU ventilators. The Fabius, Primus, and Avance are “piston ventilators,” which use an electric motor to compress gas in the breathing circuit, creating the driving force for mechanical insufflation to proceed. Therefore, they use no driving gas and may be used without depleting the oxygen cylinder in case of oxygen pipeline failure. These features may explain in part that these more recent anesthesia ventilators have comparable performance to modern ICU ventilators.

It is important for the users to know that the Fabius GS and the Fabius Tiro have the same ventilator (electrical piston) and use the same software management that regulates the ventilator. Similarly, the Primus (worldwide outside of the United States) and the Apollo (United States) anesthesia stations have the same ventilator (electrical piston). But the implemented software that regulates the ventilator is different between the Fabius GS/Tiro and Primus/Apollo. This difference may explain in part the differences in performances obtained with the two ventilators (Fabius vs. Primus).

The newer technologies used by manufacturers, i.e., microprocessors, servo valves, and fast and potent turbines, have substantially improved both modern anesthesia and ICU ventilators regarding global trigger response. It seems that the industry has so far chosen not to invest heavily in the development of PSV on anesthesia ventilators. This might seem surprising, because PSV has been available on ICU ventilators for more than 20 yr. Two main factors probably account for this. The first is of a technical nature. Indeed, an anesthesia ventilator is composed of two circuits, one for driving gas, the other for the patient circuit with the anesthetic gases, with independent bellows, and the resultant large internal volume makes it more difficult to implement fast-responding and efficient triggering mechanisms. The second factor is mainly clinical, i.e., that whereas ICU ventilators need to provide a mode of partial ventilatory support tailored to the patient’s breathing pattern during weaning, the need for such a mode in anesthesia has only become apparent in recent years. The need is probably linked to the use of laryngeal masks, which is a spontaneous-assisted mode with leaks resembling non-in...
vasive ventilation in some aspects, and the increasing use of local–regional anesthesia combined with light sedation during which spontaneous breathing is maintained.

Pressure-support ventilatory modes have recently been introduced as readily available options on newer anesthesia ventilators. Unlike ICU ventilators, which vent exhaled gases to the atmosphere and directly release gas from the wall outlet into the circuit, anesthesia ventilators recirculate exhaled gases into the inspiratory limb. It has been suggested but never evaluated that in pressure-support mode, this feature mandates a large internal volume, which may in turn alter the performance of triggering and pressurization systems.5,23 In the current study, we did not find a significant difference for the performance of triggering and pressurization systems between a low (1 l/min) and a high (10 l/min) fresh gas flow for all anesthesia ventilators and all tested dynamic conditions.

We tested the influence of PEEP on the quality of the trigger and pressure delivering because recent studies suggested that use of PEEP may have some benefits on pulmonary function.24–28

Limitations

The most important limitation of this study is the fact that it was performed on a lung model instead of in patients. It is possible that performance in patients may differ greatly from the performance demonstrated here. The advantage of the model is that mechanical characteristics can be standardized and reproduced. In addition, the test lung was modified to simulate spontaneous breathing. Hence, the different machines were tested under similar conditions during dynamic experiments. However, it is clear that these laboratory conditions are not real life and, therefore, that the results of these bench studies should be extrapolated to patients with caution. Therefore, a clinical study evaluating these characteristics and other aspects of the performance of anesthesia ventilators, e.g., on gas exchange and comfort in the operating room, should be performed. In addition, and perhaps more importantly, little is known about the validated indications of PSV in anesthetized patients. Further exploration of this topic is clearly warranted.

Conclusion

For the five tested anesthesia ventilators, PSV functioned correctly. The efficiency of delivering PSV for the anesthesia ventilators is acceptable, comparable to older-generation ICU ventilators (i.e., Servo 900C); however, it did not reach the level of performance of the new-generation ICU ventilators for three of the five tested anesthesia ventilators.

The use of PEEP modified the quality of delivered pressure support for two anesthesia ventilators (Kion and Felix). Increasing fresh gas flow (1 to 10 l/min) in the internal circuit did not influence PSV performance of the tested anesthesia ventilators. Regarding trigger sensitivity and the system’s ability to meet inspiratory flow during pressure-supported breaths, the most recent anesthesia ventilators have performances comparable to those of the modern ICU ventilators. Further clinical studies should now be conducted to better define the indications of PSV during anesthesia.

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