# A Bench Study of Intensive Care Unit Ventilators: New versus Old and Turbine-Based versus Compressed Gas-Based Ventilators

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## ABSTRACT

**Objective:** To compare 13 commercially available, new-generation, intensive-care-unit (ICU) ventilators regarding trigger function, pressurization capacity during pressure-support ventilation (PSV), accuracy of pressure measurements and expiratory resistance. **Design and Setting:** Bench study at a research laboratory in a university hospital. **Material:** Four turbine-based ventilators and nine conventional servo-valve compressed-gas ventilators were tested using a two-compartment lung model. **Results:** Three levels of effort were simulated. Each ventilator was evaluated at four PSV levels (5, 10, 15, and 20 cm $H_2O$), with and without positive end-expiratory pressure (5 cm $H_2O$). Trigger function was assessed as the time from effort onset to detectable pressurization. Pressurization capacity was evaluated using the airway pressure-time product computed as the net area under the pressure-time curve over the first 0.3 s after inspiratory effort onset. Expiratory resistance was evaluated by measuring trapped volume in controlled ventilation. Significant differences were found across the ventilators, with a range of triggering-delay from 42 ms to 88 ms for all conditions averaged ($P<0.001$). Under difficult conditions, the triggering delay was longer than 100 ms and the pressurization was poor with five ventilators at PSV5 and three at PSV10, suggesting an inability to unload patient's effort. On average, turbine-based ventilators performed better than conventional ventilators, which showed no improvement compared to a 2000 bench comparison. **Conclusion:** Technical performances of trigger function, pressurization capacity and expiratory resistance vary considerably across new-generation ICU ventilators. ICU ventilators seem to have reached a technical ceiling in recent years, and some ventilators still perform inadequately.

**Key words:** Mechanical ventilation, Pressure-support ventilation, Work of breathing, Inspiratory trigger, Bench study.

# INTRODUCTION

An important objective of assisted mechanical ventilation is synchronization of the ventilator breath with the patient's inspiratory effort, which optimizes comfort and minimizes work of breathing [1]. Pressure-support ventilation (PSV) is now widely used, most notably for weaning [2] and for noninvasive ventilation [3, 4]. Although ideally the ventilator detects the patient's effort immediately and supplies the flow that matches the patient's ventilatory needs, major patient-ventilator asynchrony is common [5, 6]. Moreover, inspiratory and expiratory delays seem to be the rule [7, 8], despite markedly improved performances of new-generation intensive-care-unit (ICU) ventilators [9]. Several lung-model studies suggest that technical differences across ICU or home ventilators may markedly affect clinical performance, especially regarding trigger function and pressurization [9-14]. Thus, differences in the effort needed to trigger the ventilator [15, 16] and in the quality of pressurization [17-20] have a clinically relevant impact on the patient's work of breathing. Although no studies specifically designed to evaluate the impact of ventilator performance on clinical outcomes are available, ICU ventilators have improved over the last two decades, and a new generation of ICU ventilators has been introduced in recent years. Competition among manufacturers is conducive to improvements in ventilators and ventilation modes, but performance may have reached a ceiling.

The purpose of our study was to compare the performances of new-generation ICU ventilators on a bench test. We compared trigger function, pressurization capacity and accuracy of pressure measurements during simulated PSV, and expiratory resistance was evaluated during volume controlled ventilation. The results were compared to those obtained 6 years earlier in a similar bench study.

The preliminary results of this study were presented at the 2006 meeting of the European Society of Intensive Care Medicine [21].

## METHODS

### Test lung

Each ventilator was connected to a validated two-chamber Michigan test lung that simulated spontaneous ventilation (Training Test Lung: Michigan Instruments, Grand Rapids, MI). The test lung is composed of two chambers linked by a rigid metal piece. The first chamber is connected to a driving ventilator (PB 7200, Puritan-Bennett, Carlsbad, CA) and the second chamber to the test ventilator. The positive pressure insufflated by the driving ventilator into the first chamber (driving chamber) produces a negative pressure in the second chamber (pressurized chamber), which is detected as an inspiratory effort by the test ventilator. We adjusted the magnitude and duration of the simulated inspiratory effort by changing the settings on the driving ventilator.

A Fleisch No. 2 pneumotachograph was inserted between the test lung and the ventilator. The differential pressure across the pneumotachograph was measured and integrated to obtain the volume (Validyne MP45, ±2.5 cm $H_2O$, Northridge, CA). Airway pressure was measured at the distal end of the circuit, using a differential pressure transducer (Validyne MP45, ±80 cm $H_2O$). Signals were acquired online using an analog-digital converter (MP100; Biopac systems, Goleta, CA), sampled at 200 Hz, and stored in a laptop computer for subsequent analysis (Acqknowledge software, Biopac systems).

### Ventilators

We evaluated all the new-generation ICU ventilators proposed by manufacturers in response to an invitation to tender for the provision of equipment to the teaching hospital network of the Paris metropolis (Assistance Publique-Hôpitaux de Paris) in 2006, namely, Avea and Vela (Viasys Healthcare, Conshohocken, PA), E 500 (Newport Medical Instruments, Costa Mesa, CA), Elisée 350 (Resmed-Saime, North Ryde, Australia), Engström and Centiva (General Electric, Fairfield, CO), Esprit (Respironics, Murrysville, PA), Extend (Taema, Antony, France), Savina and Evita XL (Dräger, Lübeck, Germany), Galileo (Hamilton, Rhäzuns, Switzerland), PB 840 (TYCO, Carlsbad, CA), and Servo I (Maquet, Solna, Sweden). Of these 13 ventilators, four were turbine-based (Elisée 350, Esprit, Savina, Vela) and nine were conventional servo-valve compressed-gas ventilators. Seven were considered as ICU ventilators (Avea, Evita XL, Engström, Extend, Galiléo, PB 840, Servo I) and six were mid-level ICU ventilators [14] (Centiva, E 500, Elisée 350, Esprit, Savina, Vela).

### Comparison of two generations of ICU ventilators (2000 and 2006)

We compared these new-generation of mid-level and ICU ventilators commercially available in 2006 with ICU ventilators available in 2000 that were tested by Richard et al. using the same bench test in the same laboratory [9], namely, Evita 2, Evita 2 Dura, and Evita 4 (Dräger, Lübeck, Germany); Servo 300 (Siemens-Elema, Solna, Sweden); PB 840 (Puritan-Benett, Carlsbad, CA, USA); Galileo (Hamilton, Rhäzuns, Switzerland); and Horus (Taema, Antony, France). We chose to compare these two generations of ventilators under the most difficult conditions in terms of performance. The test conditions were exactly the same during the two studies (weak effort for evaluating trigger function and low PSV level with a very strong effort for evaluating pressurization capacity).

## Design of the experiment

Each ventilator was evaluated during simulated PSV at four levels of pressure-support (5, 10, 15, and 20 cm $H_2O$), with and without 5 cm $H_2O$ positive end-expiratory pressure (PEEP), at three levels of simulated inspiratory effort (weak, strong, and very strong), for a total of 24 conditions. On all the test ventilators, the inspiratory trigger was set at the highest sensitivity that was not associated with auto-triggering. A less sensitive inspiratory trigger was required using PEEP due to auto-triggering (1.3±0.8 L/min versus 0.8±0.3 L/min, $P<0.01$). The pressurization rate can directly influence pressurization capacity and the fastest value was set on all ventilators except for Vela (not adjustable) and Centiva (due to overshoot).

To simulate different magnitudes of inspiratory effort by patients, the tidal volume of the driving ventilator was set at 100, 600, or 1200 ml with an inspiratory flow of 0.1, 0.6, or 1.2 L/s, respectively, replicating weak, strong, and very strong respiratory drives. Occlusion for 0.1 s was associated with a pressure drop ($P_{0.1}$) of 2 (weak effort), 6 (strong effort), or 13 (very strong effort) cm $H_2O$. $P_{0.1}$ is about 2 cm $H_2O$ during normal efforts by healthy individuals and during full assistance [22], whereas a very strong effort by a patient with acute respiratory failure can generate $P_{0.1}$ values greater than 10 cm $H_2O$ [23]. A decelerating flow was used to create the maximal flow demand at breath onset, as often observed in patients [24]. High compliance (100 ml/cm $H_2O$) and low resistance (5 cm $H_2O/L\cdot s^{-1}$) were adjusted in the chamber connected to the test ventilator. Generating a high flow demand in a system with high compliance and low resistance simulates a critical condition requiring the ventilator to deliver a high peak flow rate to reach and maintain the set pressure.

## Evaluation of trigger performance *(Figure 1A)*

We used two criteria to assess trigger performance.

- Triggering delay (DT), in ms, defined as the time from the beginning of the patient's effort to the beginning of ventilator pressurization. A shorter delay indicates better trigger performance. In reality, true ventilator's response occurs few ms before the maximal airway pressure drop but the nadir point is easier to measure and allows a fair comparison between ventilators.
- Inspiratory delay (DI), in ms, defined as the time during which airway pressure remains negative (or below baseline when using PEEP). DI is the sum of DT and of the pressurization delay (DP) from $\Delta P$ to the return to baseline pressure.

  Consequently, DI depends on both trigger function and pressurization quality.

At the onset of the inspiratory effort, airway pressure falls below PEEP until it reaches the trigger threshold. Then, airway pressure increases, becoming greater than PEEP when the flow delivered by the ventilator overcomes the flow related to the inspiratory effort. The initial phase during which airway pressure is below PEEP can be seen as an imposed inspiratory load, whereas the airway pressure increase above PEEP represents the start of mechanical unloading.

### Dynamic evaluation of pressure-support ventilation *(Figure 1B)*

To assess pressurization performance, we computed the airway pressure-time product (PTP, cm $H_2O{\cdot}s$) as the net area under the pressure-time curve (below and above PEEP) over the first 0.3 s following the onset of the inspiratory effort (Figure 1B). PTP represents the amount of assistance received by the patient during the initial part of the effort and reflects the initial efficacy of pressurization, including trigger performance [9]. A larger PTP value indicates better pressurization. PTP was suggested as an index of pressurization performance because most of the breath triggered by the inspiratory effort usually occurs during the early part of inspiration [24]. The triggering phase represents only a small part of the total inspiratory effort, being far shorter than the pressurization phase [15].

The accuracy of the ventilator to deliver the adequate pressure support was evaluated by measuring the delivered pressure support using all preset pressure support levels (5, 10, 15 and 20 $cmH_2O$).

### Expiratory resistance

To assess resistance induced by expiratory valve system we measured the amount of exhaled volume at different expiratory time after the end of insufflation of the preset tidal volume. Ventilators were tested in controlled ventilation with a tidal volume of 500 ml, a flow rate of 30 L/min and an insufflation time of 1 s. Ventilators were connected to a Test lung 190 (Maquet, Solna, Sweden) characterized by a resistance of 20 $cmH_2O/L.s$. Expiratory resistance was evaluated by measuring the trapped volume at 0.7 and 1.4 s after the end of insufflation. A smaller trapped volume indicates less expiratory resistance and better performance.

### Statistical analysis

Each parameter value represents the mean of values measured for five breaths after reaching the steady state. All results are reported as mean ± standard deviation. We used one-way analysis of variance to compare DT, DI, PTP and expiratory resistance across ventilators and to evaluate the impact of PEEP and effort level on trigger function and pressurization quality. Turbine-based ventilators and conventional servo-valve compressed-gas ventilators were compared for each parameter using unpaired Student's *t*-tests. To compare the two generations of ICU ventilators (2006 and 2000), we used a nonparametric Friedman test, given the small number of conditions. *P* values smaller than 0.05 were considered statistically significant.

## RESULTS

### Trigger function (Figures 2, E1 and E2)

Triggering delay (DT) differed significantly across ventilators ($P<0.001$). When all conditions were averaged, mean DT was 58 ms (range, 42-88 ms) ***(Figure 2)***. Mean DT was shorter than 50 ms with five ventilators (Elisée 350, Esprit, Engström, PB 840 and Servo I). DT was significantly longer (indicating lower trigger sensitivity) during weak efforts (69±31 ms versus 52±14 during strong efforts and 52±15 during very strong efforts, $P<0.001$) and during PEEP application (62±26 ms versus 54±18 without PEEP, $P=0.002$). The pressure-support level had no influence on DT ($P=0.58$). Under difficult conditions (weak efforts), DT was greater than 100 ms with two ventilators (Avea and Evita XL) ***(Figure E1)***.

Inspiratory time delay (DI) differed significantly across ventilators ($P<0.001$). When all conditions were averaged, mean DI was 94 ms (range, 54-177 ms) ***(Figure 2)***. Mean DI was shorter than 70 ms with five ventilators (Elisée 350, Esprit, Engström, PB 840, and Servo I). DI was significantly longer during very strong efforts (107±65 ms versus 88±46 during strong efforts and 86±38 during weak efforts, $P<0.01$) and with a low level of pressure support (122±67 ms with 5 cm $H_2O$ versus 93±48 with 10 cm $H_2O$, 81±38 with 15 cm $H_2O$, and 80±36 with 20 cm $H_2O$, $P<0.001$). PEEP application had no significant influence on DI (99±53 ms versus 89±50 without PEEP, $P=0.10$). Under difficult conditions (very strong efforts), DI was greater than 100 ms with six ventilators (Avea, Centiva, E 500, Extend, Galileo, and Vela). Under the worst conditions (very strong efforts and low level of pressure support), DI was greater than 200 ms with four ventilators (Avea, Centiva, E 500, and Vela). However, DI under the worst conditions remained lower than 100 ms with four ventilators (Elisée 350, Engström, PB 840, and Savina), indicating sensitive triggering and high pressurization capacity.

### Pressurization capacity *(Figures 3 and E3)*

PTP differed significantly across ventilators ($P<0.001$). When all conditions were averaged, mean PTP was 1.6 cm $H_2O$ (range, 0.1 cm $H_2O$ for the worst pressurization to 2.6 cm $H_2O$ for the best pressurization) ***(Figure 3)***. PTP was not influenced by PEEP application (1.6±1.3 versus 1.6±1.3 cm $H_2O$, $P=0.78$) or effort intensity (1.6±1.1 cm $H_2O$ during weak efforts, 1.8±1.3 cm $H_2O$ during strong efforts, and 1.4±1.4 cm $H_2O$ during very strong efforts, $P=0.20$). Under difficult pressurization conditions (5 cm $H_2O$ of ventilatory assistance and very strong effort), PTP remained negative with several ventilators, indicating failure of the ventilator to unload the first 0.3 s of the effort (***Figure E3)***. Increasing the pressure-support level increased PTP. PTP remained negative with three ventilators (Avea, Centiva, and E500) at a pressure-support level of 10 cm $H_2O$ and with one ventilator (Centiva) at a pressure-support level of 15 cm $H_2O$.

### Delivered pressure support *(Figure 4)*

The difference between the preset and the delivered pressure support was greater than 10% in 4 ventilators (Avea, E 500, extend, PB 840) ***(Figure 4)***. This error occurred using all levels of pressure support tested (5 to 20 cm$H_2O$). The delivered pressure support was higher than preset in only two ventilators (Avea and Galileo).

### Expiratory resistance *(Figure 5)*

Expiratory resistance differed significantly across ventilators ($P$<0.001) and decreased when expiratory time was lengthened with a trapped volume of 17±9 % at 0.7 s and 5±8 % at 1.4 s ($P$ <0.001). The trapped volume at 0.7 s was greater than 20% in 3 ventilators (Avea, Engström, and Vela), between 10 and 20% in 8 ventilators (Centiva, E 500, Elisée 350, Esprit, Evita XL, Extend, Galileo and PB 840) and lower than 10% in 2 ventilators (Savina and Servo I) ***(Figure 5)***. The trapped volume at 1.4 s remained greater than 30% in only one ventilator (Avea). Application of PEEP had no influence on expiratory resistance (17±9 % at 0.7 s and 6±10 % at 1.4 s versus 17±9 % and 4±6 % without PEEP, $P$=0.50).

### Comparison of turbine-based ventilators and compressed gas-based ventilators *(Figure 6)*

On average, trigger function and pressurization quality were better with the four turbine-based ventilators than with the nine conventional servo-valve compressed-gas ventilators ***(Figure 6)***. Turbine-based ventilators had a shorter mean DT (51±15 ms versus 61±25 ms, $P$=0.001) and a shorter mean DI (76±34 ms versus 102±56 ms, $P$<0.001). Mean PTP was higher with the turbine-based ventilators than with the conventional servo-valve ventilators (1.8±1.1 cm $H_2O$ versus 1.5±1.3 cm $H_2O$, $P$=0.03).

### Changes in ICU ventilators since the earlier bench comparison *(Figure 7)*

The mean DT evaluated under difficult conditions (weak efforts) was similar with the 2000 ventilators than with the 2006 ventilators (52±5 ms versus 72±17 ms and 67±18 ms for ICU and mid-level ICU in 2006, $P$=0.14) ***(Figure 7)***. Pressurization capacity under difficult conditions (low level of pressure support and very strong efforts) tended to be poorer with the 2006 ventilators, although the difference was not significant (PTP was 0.4 ±0.1 cm $H_2O$ in

2000 versus 0.1±0.4 and -0.1±0.8 cm $H_2O$ for ICU and mid-level ICU ventilators respectively, *P*=0.11) ***(Figure 7)***.

## DISCUSSION

We used a lung model to test a large number of ICU ventilators. Trigger function and pressurization quality varied substantially during PSV. Some ventilators responded poorly to difficult conditions, exhibiting a long triggering-delay during simulated weak efforts or inadequate pressurization during simulated strong efforts with low levels of pressure support. New-generation turbine-based ventilators performed as well as, or better than, the best compressed-gas ventilators. The new ventilators did not perform significantly better than the 2000 ventilators, suggesting that a technological ceiling may have been reached.

### Triggering function

During PSV, the effort required to trigger the ventilator represents 10%-20% of the breathing effort [15]. With most ICU ventilators, the triggering system relies on flow detection. In general, the patient effort needed to trigger the ventilator is smaller with flow-triggering than with pressure-triggering systems [15, 25-28]. Furthermore, a sensitive detection threshold may improve patient-ventilator synchrony by minimizing ineffective triggering [5]. Greater trigger sensitivity is associated with shorter delays to detection of patient efforts (DT). We found that mean DT was shorter than 100 ms with all the new-generation ventilators, in keeping with studies of recently introduced ICU ventilators [9, 11], anesthesia ventilators [10], or ventilators used during transport of ICU patients [29]. However, several ventilators exhibited values greater than 100 ms under difficult conditions (weak effort). Such long DT values can be observed with older ICU ventilators [9], mid-level ICU ventilators [14], home ventilators [12], or transport ventilators [30]. DT, which depends only on trigger function, was longest during weak efforts and with PEEP. Indeed, a less sensitive inspiratory trigger was set using PEEP due to auto-triggering. A weak effort generates a small drop of pressure which is logically more difficult to detect.

### Pressurization capacity

At a given pressure-support level, the ventilator must deliver a high initial flow when the patient's effort increases, i.e., must exhibit good pressurization capacity. Studies evaluating the impact of peak flow rate on patient effort showed that patient work of breathing decreased markedly when the time to reach the set pressure was short [18-20]. Mancebo et al. compared patient effort across three ventilators at the same level of pressure-support [17]. Marked differences in patient effort were found, although the ventilator settings were similar. Work of breathing was halved with a high-performance ventilator, compared to a ventilator whose pressurization capacity failed to meet the patient's ventilation demand [17]. Here, we found that airway pressure could remain negative for more than 0.3 s, during which the patient's inspiratory effort was not unloaded by the ventilator. Such inadequate pressurization capacity is highly undesirable during mechanical ventilation.

### Changes in ICU ventilators and turbine-based ventilators

Richard et al. reported significant improvements in the performance of ICU ventilators available in 2000, compared to those available in 1993 [9]. The ventilators available in 2000 and in 2006 were evaluated using the same test protocol, in the same laboratory. No significant improvements occurred between 2000 and 2006. Instead, some of the newer ventilators exhibited poor performance characteristics similar to those of older machines. AVEA showed poorer performances on some of the tests, but when this ventilator was removed from the 2006 ICU ventilators for further comparisons, the overall comparison between 2002 and 2006 remained similar. Moreover, mean DT was about 40-50 ms with the best ICU ventilators available in 2006, which was very similar to the values measured in 2000. Currently available technologies may be unable to further decrease the DT. In 2000, performances of turbine-based ventilators were slightly lower than those of recent compressed-gas ICU ventilators [9]. We found that turbine-based ventilators had better trigger function and pressurization than compressed-gas ventilators. However, we evaluated only the best turbine-based ventilators, since the machines were intended for ICUs, as opposed to noninvasive ventilation only. The performances of these turbine-based ventilators were similar to those of the best compressed-gas ICU ventilators. Thus, current turbine-based ventilators perform as well as the best conventional ICU ventilators.

### Clinical implications and limitations of the study

The study was performed using a lung model whose advantages include standardization of mechanical characteristics, repeatability of ventilator tests, and an ability to study a broad range of situations. The lung model may closely replicate the patient's work of breathing during assisted mechanical ventilation. In a study involving both test-lung experiments and investigations in patients, simulated breathing effort during PSV was significantly less with flow triggering than with pressure triggering, and flow triggering was associated with significant reductions in all indices of patient work of breathing [15]. Thus, differences found with the test lung predicted clinical differences in patient work of breathing. The clinical relevance of statistically significant differences across ventilators may be difficult to determine (e.g., the clinical relevance of the difference between a triggering delay of 40 ms vs. 50 ms is unclear). In the above-mentioned study [15], lengthening DT from 89 to 155 ms significantly increased patient work of breathing by about 15%, from 10.5 to 12.2 Joules/min. Trigger function, pressurization quality represent only part of the technical performance of the ventilator during PSV. We tested gas trapping due to expiratory resistance, which reflects the ventilator‘s ability to decompress the circuit during exhalation (function of the expiratory valve), but the cycling off mechanism was not specifically studied. New modes specifically dedicated for noninvasive ventilation (working with leaks) have been implemented on most ICU ventilators with heterogeneous results [31]. We did not evaluate this important function which requires a specific bench model.

## Conclusion

Technical performances of new-generation ICU ventilators vary widely in terms of trigger function and pressurization quality during PSV. These variations may be associated with differences in patient work of breathing and patient-ventilator interactions during assisted mechanical ventilation. New-generation turbine-based ventilators perform as well as the best compressed-gas ICU ventilators. Trigger function and pressurization quality showed no significant improvements between ventilators available in 2000 and those available in 2006, suggesting that a technological ceiling may have been reached. Several ventilators show inadequate performance characteristics likely to result in inadequate quality of care for ventilated ICU patients.

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## FIGURE LEGENDS

**Figure 1A: Evaluation of trigger performance**

Pressure signal showing the inspiratory delay (DI), which is the sum of the triggering delay (DT) from the beginning of the simulated patient effort to the beginning of ventilator pressurization and of the pressurization delay (DP) from the maximal airway pressure drop ($\Delta P$) to the return to baseline pressure.

**Figure 1B: Evaluation of pressurization capacity**

Pressure signal showing the pressurization capacity represented by the positive area over the first 0.3 s of the simulated patient effort (black hatched area). The red signal illustrates poor pressurization capacity: the time needed to reach the set pressure is longer and the positive area is smaller.

**Figure 2:**

Inspiratory delay (DI) is displayed with its two components, triggering delay (DT) and pressurization delay (DP), for each ventilator. A shorter DI value indicates better trigger performance. Values are mean ± standard deviation for each of 24 conditions (four levels of pressure-support [5, 10, 15, and 20 cm $H_2O$], three effort intensities [weak, strong, and very strong], and two levels of positive end-expiratory pressure [0 and 5 cm $H_2O$]). The mean value for the 13 ventilators tested in 2006 (including 6 mid-level ICU ventilators) and the 7 ICU ventilators are shown at the far left.

**Figure 3:**

Pressure-time product (PTP) for each ventilator. PTP was assessed as the positive area over the first 0.3 s of the inspiratory effort. Higher PTP values indicate better pressurization.

Values are mean±standard deviation for each of 24 conditions (four levels of pressure-support [5, 10, 15, and 20 cm $H_2O$], three effort intensities [weak, strong, and very strong], and two levels of positive end-expiratory pressure [0 and 5 cm $H_2O$]). The mean value for the 13 ventilators tested in 2006 (including 6 mid-level ICU ventilators) and the 7 ICU ventilators are shown at the far left.

**Figure 4:**

Figure showing the true delivered pressure support at different levels of pressure support. Each ventilator was tested for a preset pressure support of 5, 10, 15 and 20 cm $H_2O$.

**Figure 5:**

Expiratory resistance for each ventilator evaluated by the trapped volume at 0.7 s and 1.4 s of expiratory time (expressed in percentage of insufflated volume). Lower trapped volumes indicate lower expiratory resistance and better performance.

**Figure 6:**

Comparison of the nine compressed-gas ventilators (black squares) and the four turbine-based ventilators (white squares) regarding trigger performance assessed on triggering delay (DT) and pressurization capacity assessed as the pressure-time product (PTP) over the first 0.3 s after the start of the simulated effort. Trigger performance and pressurization capacity were significantly better with the turbine-based ventilators.

**Figure 7:**

Comparison of the seven ICU ventilators in 2000 (white squares) with the seven ICU ventilators and the six mid-level ICU ventilators in 2006 (black squares) regarding trigger performance assessed on triggering delay (DT) and pressurization capacity assessed as the pressure-time product (PTP) over the first 0.3 s after the start of the simulated effort. A shorter DI value indicates better trigger performance and a higher PTP values indicate better pressurization. We found no significant differences and performances tended to be poorer in 2006.

**Figure 1:**

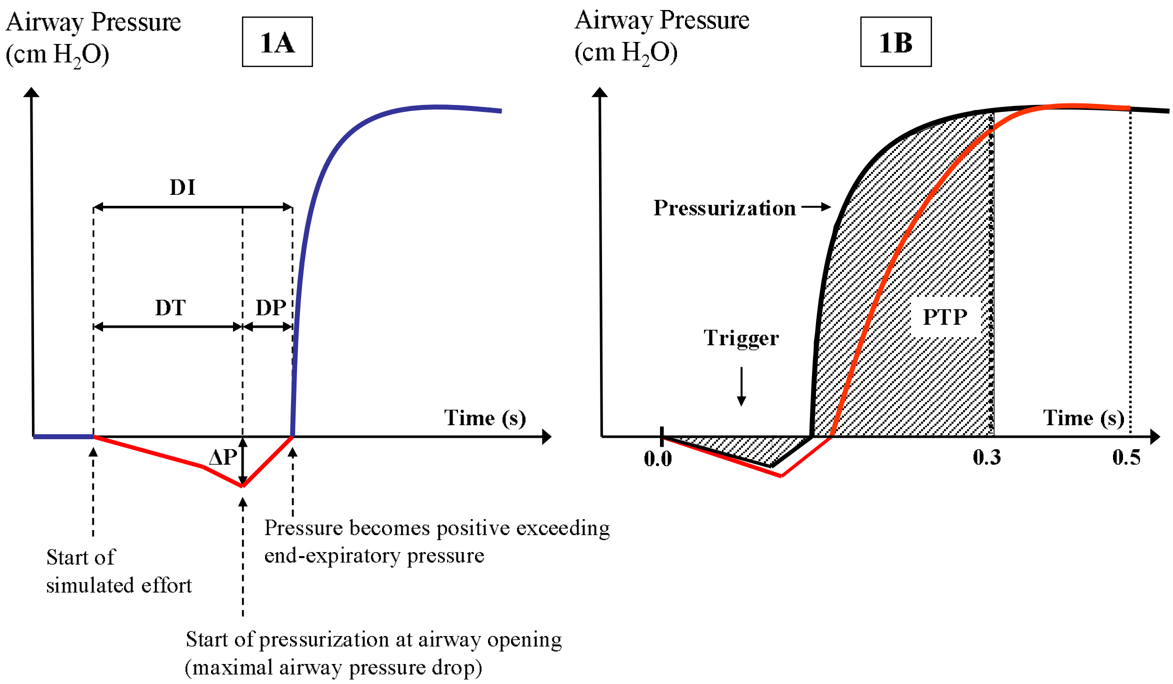

Airway Pressure
(cm $H_2O$)
1A
DI
DT
DP
Time (s)
ΔP
Start of
simulated effort
Pressure becomes positive exceeding
end-expiratory pressure
Start of pressurization at airway opening
(maximal airway pressure drop)
Airway Pressure
(cm $H_2O$)
1B
Pressurization
Trigger
PTP
Time (s)
0.0
0.3
0.5

**Figure 2:**

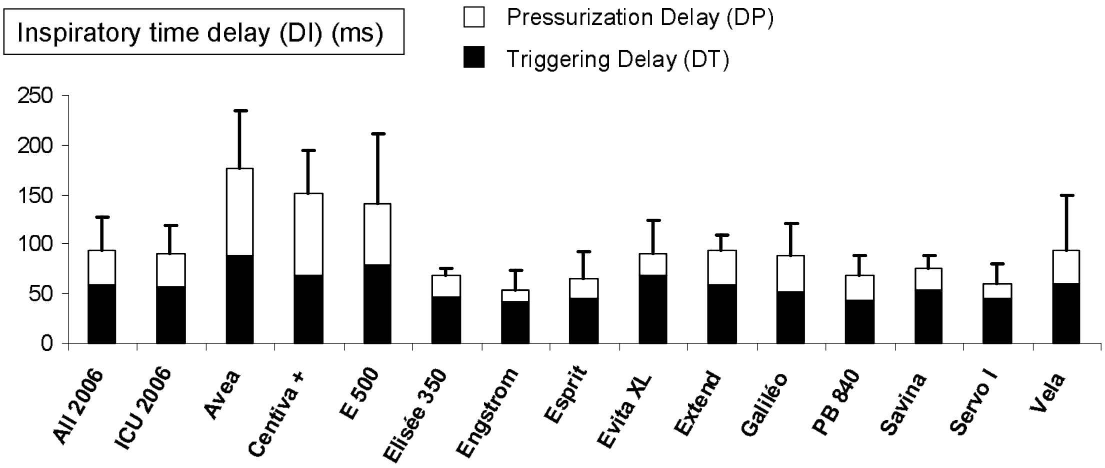

Inspiratory time delay (DI) (ms)
☐ Pressurization Delay (DP)
■ Triggering Delay (DT)
250
200
150
100
50
0
All 2006
ICU 2006
Avea
Centiva +
E 500
Elisée 350
Engstrom
Esprit
Evita XL
Extend
Galiléo
PB 840
Savina
Servo I
Vela

**Figure 3 :**

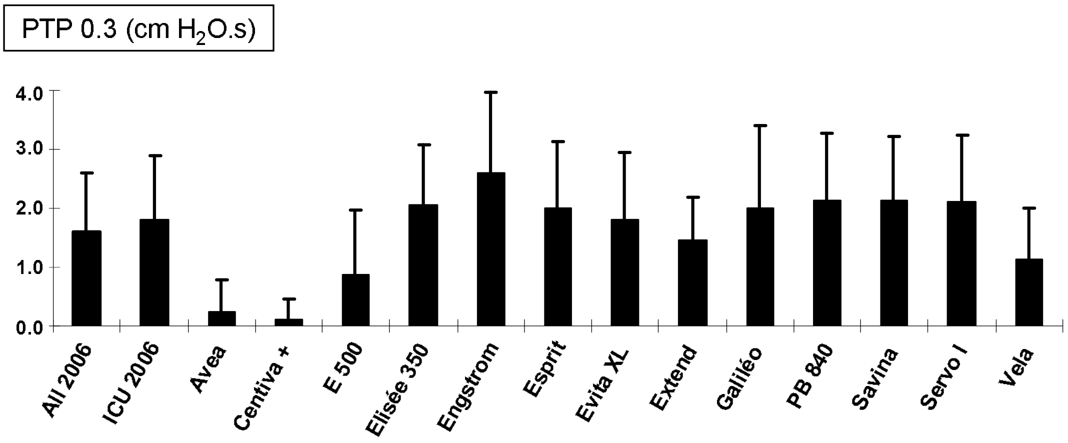

PTP 0.3 (cm $H_2O$.s)
4.0
3.0
2.0
1.0
0.0
All 2006
ICU 2006
Avea
Centiva +
E 500
Elisée 350
Engstrom
Esprit
Evita XL
Extend
Galiléo
PB 840
Savina
Servo I
Vela

**Figure 4 :**

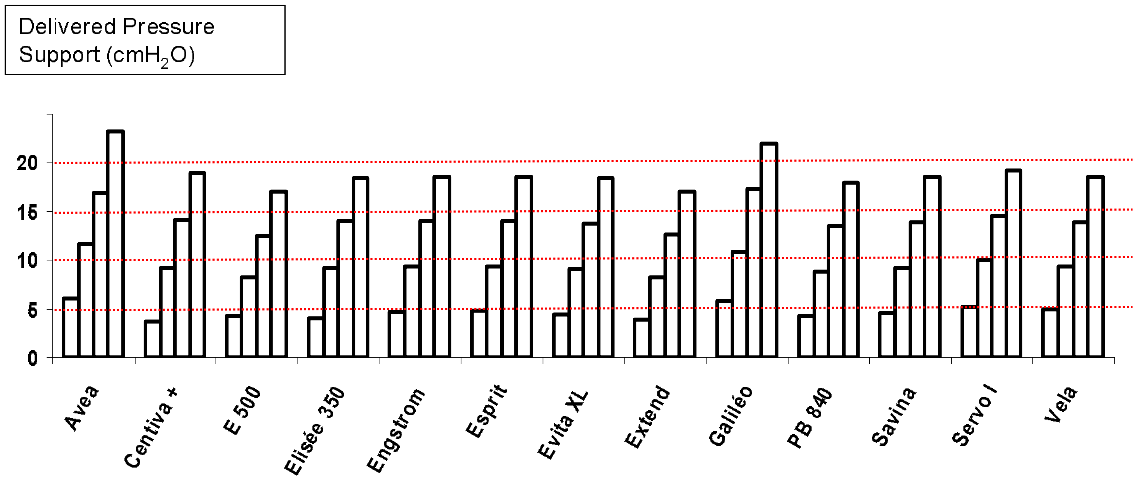

Delivered Pressure Support (cmH2O)
0
5
10
15
20
Avea
Centiva +
E 500
Elisée 350
Engstrom
Esprit
Evita XL
Extend
Galiléo
PB 840
Savina
Servo I
Vela

**Figure 5 :**

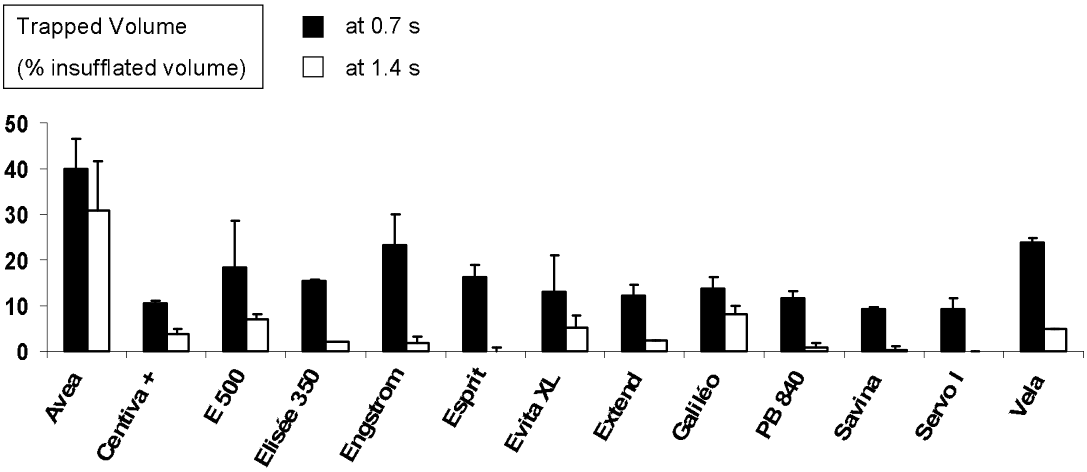

Trapped Volume
(% insufflated volume)
■ at 0.7 s
□ at 1.4 s
50
40
30
20
10
0
Avea
Centiva +
E 500
Elisée 350
Engstrom
Esprit
Evita XL
Extend
Galiléo
PB 840
Savina
Servo I
Vela

**Figure 6:**

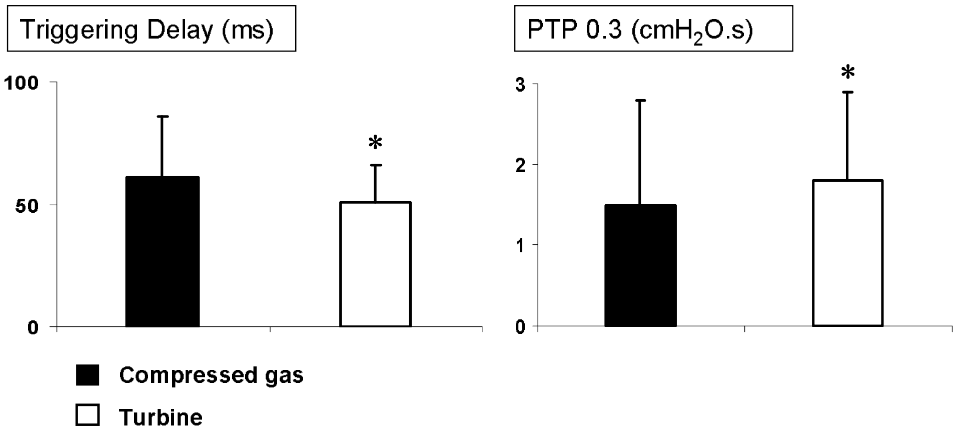
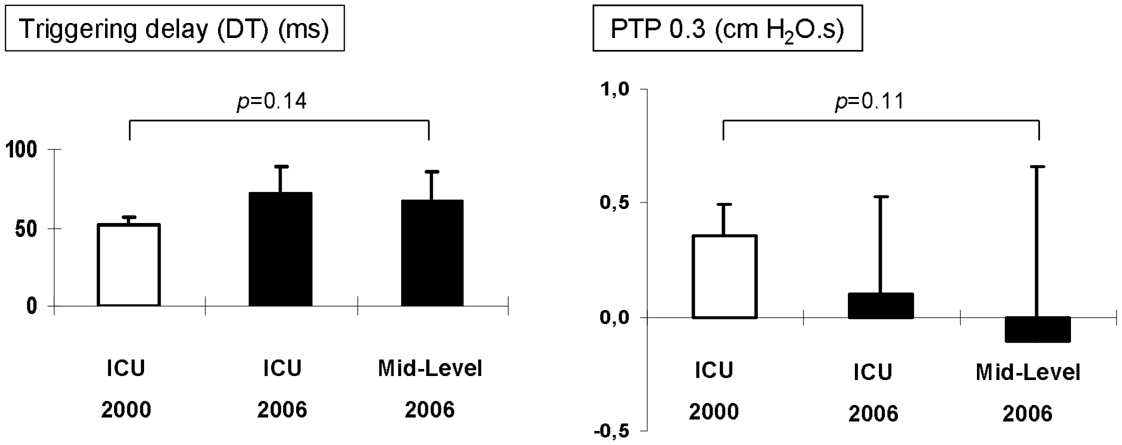

Triggering Delay (ms)
100
50
0
*
PTP 0.3 ($cmH_2O.s$)
3
2
1
0
*
Compressed gas
Turbine

**Figure 7 :**


Triggering delay (DT) (ms)
p=0.14
100
50
0
ICU 2000
ICU 2006
Mid-Level 2006
PTP 0.3 (cm H2O.s)
p=0.11
1,0
0,5
0,0
-0,5
ICU 2000
ICU 2006
Mid-Level 2006