

## Evaluation of Inspiratory Rise Time and Inspiration Termination Criteria in New-Generation Mechanical Ventilators: A Lung Model Study

Sunisa Chatmongkolchart MD, Purris Williams RRT, Dean R Hess PhD RRT FAARC, and Robert M Kacmarek PhD RRT FAARC

**INTRODUCTION:** Inspiratory rise time adjustment during pressure ventilation and inspiration termination criteria adjustment during pressure support ventilation are available on some of the newest mechanical ventilators. Both are designed to improve patient-ventilator synchrony. However, the function of these adjuncts during pressure ventilation on these ventilators has not been evaluated. **METHODS:** Three inspiratory rise times (minimum, medium, and maximum) were evaluated in 5 new-generation mechanical ventilators (Hamilton Galileo, Siemens 300A, Puritan Bennett 840, BEAR 1000, and Dräger Evita 4) during pressure support and pressure assist/control. Three inspiration termination criteria settings (minimum, medium, and maximum) were also evaluated in 2 mechanical ventilators (Hamilton Galileo and Puritan Bennett 840) during pressure support. All evaluations were performed with a spontaneous breathing lung model (compliance 50 mL/cm H<sub>2</sub>O, resistance 8.2 cm H<sub>2</sub>O/L/s, respiratory rate 12 breaths/min, inspiratory time 1.0 s, and lung model peak inspiratory flow 60 L/min). Throughout the evaluation, inspiratory pressure was set at 15 cm H<sub>2</sub>O and positive end-expiratory pressure at 5 cm H<sub>2</sub>O, resulting in a peak airway pressure of 20 cm H<sub>2</sub>O. **RESULTS:** Significant ( $p < 0.05$ ) and important ( $> 10\%$ ) differences were found among the ventilators at similar rise times (minimum, medium, and maximum) and for each ventilator as rise time was varied. Also, significant ( $p < 0.05$ ) and important ( $> 10\%$ ) differences were observed between ventilators and within each ventilator when inspiration termination criteria were varied. There were significant ( $p < 0.05$ ) differences between pressure support and pressure assist/control, but most were  $< 10\%$ , except those associated with expiration. **CONCLUSIONS:** Major differences exist for each ventilator as rise time or inspiration termination criteria are varied and among ventilators at similar settings. Inspiration termination criteria adjustment markedly affects transition to exhalation in the Puritan Bennett 840. *Key words:* mechanical ventilation, inspiratory rise time, inspiration termination criteria, pressure support, pressure assist/control, flow-triggered, flow-cycled. [Respir Care 2001;46(7):666–677]

### Introduction

During patient-triggered mechanical ventilatory assistance, patient-ventilator synchrony is a major problem.

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Many investigators have demonstrated that volume ventilation commonly results in large patient efforts during patient-triggered breaths, because of fixed inspiratory flow patterns.<sup>1,2</sup> As a result, pressure ventilation (pressure support [PS] and pressure assist/control [PA/C]) has been recommended as the optimal approach to ensure patient-ventilator synchrony, because inspiratory flow delivery responds to patient demand.<sup>3,4</sup> However, as nicely illustrated by MacIntyre et al<sup>5</sup> and others,<sup>6,7</sup> dyssynchrony can also exist during pressure ventilation. If the rise in flow is not commensurate with patient demand, pressure may overshoot the set level (too rapid an increase in flow) or patient effort can be excessive (inadequate increase in flow). Both

of these extremes can result in patient-ventilatory dyssynchrony. A number of the newest generation of mechanical ventilators give the clinician the option of setting the rise time during pressure ventilation to meet patient demand.

During PS, inspiration normally cycles to expiration when inspiratory flow decreases to a level equal to a fixed percentage (eg, 25%) of the peak flow or to a specified flow (eg, 5 L/min).<sup>8</sup> However, if the patient decides to terminate inspiration before the flow criteria are met, the patient must activate abdominal muscles to force airway pressure to rise to a fixed level above the set pressure target (eg, 3 cm H<sub>2</sub>O).<sup>9</sup> This activation of the expiration muscles at the end of the inspiratory phase increases patient effort and produces dyssynchrony.<sup>5</sup> A few of the newest generation of ventilators have the ability to adjust the inspiration termination criteria.

Limited information is currently available on the function of rise time and inspiration termination criteria on the newest generation of ventilators. We evaluated the function of rise time on 5 new-generation ventilators and inspiration termination criteria on 2 new-generation ventilators. We hypothesized that there would be no differences in the operation of rise time between PS and PA/C modes on a given ventilator but that there would be large differences among ventilators evaluated. We also hypothesized that a synchronous transition to exhalation would be made possible by appropriate adjustment of the inspiration termination criteria.

## Methods

### Lung Model

All evaluations were performed with a simulated spontaneous breathing lung model, as previously described.<sup>10,11</sup> The lung model consisted of 2 parallel bellows suspended in an airtight rigid box (Fig. 1). The space in the rigid box represents the pleural space, which was connected to a low-compliance T tube through which gas flow was injected to create a negative pleural pressure ( $P_{pi}$ ). Source gas (oxygen, 50 psi) was connected to an air pressure regulator (SMC air pressure regulator model AR 2000, SMC Company, Tokyo, Japan) and a proportional solenoid valve (SMC 315, SMC Company, Tokyo, Japan). Opening of the solenoid valve was controlled by a function generator (EGC 2230, Kenwood, Tokyo, Japan). Operation of the regulator allowed adjustment of negative pressure in the pleural space and simulation of a spontaneous breathing pattern. Thus, inspiratory flow demand, respiratory rate, and inspiratory time were controlled independently. A linear resistor (7100 R-5, Hans Rudolph, Kansas City, Missouri) established a resistance of 8.2 cm H<sub>2</sub>O/L/s at a flow of 60 L/min. Compliance of 50 mL/cm H<sub>2</sub>O was set by springs on the bellows. The lung model

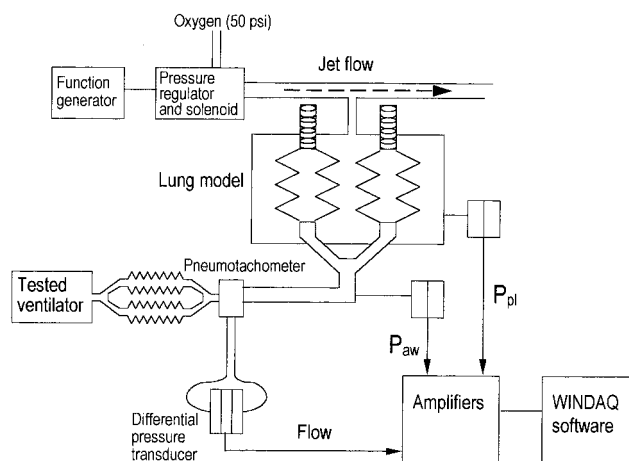


Fig. 1. Experimental set-up. See text for details.  $P_{aw}$  = airway pressure,  $P_{pi}$  = pleural pressure.

was connected to each studied ventilator using a standard ventilator circuit. A humidifier (ConchaTherm IV heated humidifier, Hudson RCI, Temecula, California) was maintained in the circuit, but active humidification was not employed.

Three inspiratory rise times (minimum, medium, and maximum) (Table 1) were studied on 5 ventilators, the Hamilton Galileo (Hamilton Medical AG, Rhazuns, Switzerland), the Siemens 300A (Siemens-Elerna, Solna, Sweden), the Puritan Bennett 840 (Puritan Bennett, Pleasanton, California), the BEAR 1000 (ThermoRespiratory Group, Palm Springs, California), and the Dräger Evita 4 (Dräger, Telford, Pennsylvania) during both PS and PA/C modes. The evaluations were performed at ventilator settings of inspiratory pressure of 15 cm H<sub>2</sub>O and positive end-expiratory pressure (PEEP) of 5 cm H<sub>2</sub>O. During PA/C mode the inspiratory time was set at 1.0 s. The lung model was always set at a respiratory rate of 12 breaths/min, inspiratory time of 1.0 s, and peak inspiratory flow of 60 L/min. The Hamilton Galileo and Puritan Bennett 840 (PB 840) were also evaluated at 3 inspiration termination criteria settings (minimum, medium, and maximum) (Table 2) in PS mode. After a period of stabilization, flow, airway pressure, and pleural pressure were recorded for a series of breaths at each experimental condition. Three consecutive breaths for each experimental setting were evaluated (Fig. 2). The inspiration termination criteria of every studied ventilator except the Galileo and the PB 840 were automatically fixed at predetermined levels by the manufacturers. The inspiration termination criteria of the Galileo and the PB 840 were set at 25% during assessment of inspiratory rise times. When the effect of the inspiration termination criteria was evaluated, the inspiratory rise time was set at the maximum: 50 ms for the Hamilton Galileo and 100% for the PB 840. All ventilators were set to flow-triggering at the most sensitive level that did not

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Table 1. Experimental Settings of Inspiratory Rise Time with Manufacturer-Recommended Settings

Ventilator	Minimum	Medium	Maximum	Manufacturer-recommended
Hamilton Galileo (pressure ramp, ms)	200	125	50	50
Siemens 300A (%)	10	5	0	1
PB 840 (flow acceleration, %)	1	50	100	50
BEAR 1000 (pressure slope)	-9	0	9	0
Dräger Evita 4 (s)	2	1	0	0.2

PB = Puritan Bennett.

result in auto-triggering. This resulted in the following settings. The Galileo inspiratory sensitivity was set at 2 L/min. The inspiratory sensitivity of the Siemens 300A was set between the green and red line (2 L/min). For the PB 840, the inspiratory sensitivity was set at 0.5 L/min, with base flow of 2 L/min. The sensitivity of the BEAR 1000 was set at 1 L/min, with bias flow of 5 L/min. For the Dräger Evita 4, the sensitivity was set at 0.3 L/min.

### Measurement and Calibration

Flow was measured at the distal end of the breathing circuit, using a pneumotachometer (model 3700 A, Hans Rudolph Inc, Kansas City, Missouri) connected to a differential pressure transducer (MP 45-14-871,  $\pm 2$  cm H<sub>2</sub>O, Validyne, Northridge, California). The pneumotachometer was calibrated with a 1 L/s flow delivered by a precision flow meter (Brooks Instruments, Hatfield, Pennsylvania). Pressures at the airway opening at the proximal end of the endotracheal tube and in the simulated pleural space ( $P_{pl}$ ) were measured with differential pressure transducers (MP 45-32-871,  $\pm 100$  cm H<sub>2</sub>O, Validyne, Northridge, California). The pressure transducers were calibrated at 20 cm H<sub>2</sub>O with a water manometer. All signals were amplified (model 8805C, Hewlett Packard, Waltham, Massachusetts), sampled at 100 Hz, digitized, and recorded with WINDAQ software (Dataq Instruments, Akron, Ohio). The WINDAQ playback system was used to analyze the data.

### Studied Variables

Variables studied are graphically illustrated in Figure 2. The beginning and end of inspiration were identified based

Table 2. Experimental Settings of Inspiratory Termination Criteria and Manufacturer-Recommended Settings

Ventilator	Minimum	Medium	Maximum	Manufacturer-recommended
Hamilton Galileo (%)	40	25	10	25
PB 840 (%)	45	25	1	10

PB = Puritan Bennett.

on changes in the simulated pleural pressure. A below-baseline deflection in pleural pressure identified the start of inspiration by the lung model. The onset of the return of pleural pressure toward baseline identified the termination of inspiration by the lung model. These pleural pressure changes were used in determining the duration of inspiration and expiration.

The following variables were measured during the inspiratory phase:

1. Inspiratory delay time. The time from the onset of inspiration until the return of the airway pressure to baseline. This represents the total delay from onset of lung model inspiration to the beginning of system pressurization. Ideally, the inspiratory delay time should be zero.

2. Inspiratory trigger time. The time from the onset of inspiration until the maximum sub-baseline trigger pressure is established. This represents the delay between initiation of inspiration and the ventilator responding with sufficient flow to stop the decline in airway pressure, indicating the responsiveness of the ventilator to patient effort. Ideally, inspiratory trigger time should be zero.

3. Time to return trigger pressure to baseline. The time from the maximum sub-baseline trigger pressure to the return of airway pressure to baseline. This represents the speed with which the ventilator pressurizes the system after patient effort is recognized and illustrates the speed with which initial flow is delivered. Ideally, the time to return trigger pressure to baseline should be zero.

4. Inspiratory trigger pressure. The pressure change from baseline to maximum sub-baseline trigger pressure. This pressure represents the pressure deflection below baseline necessary to activate the breath. Ideally, the inspiratory trigger pressure should be less than 1.0 cm H<sub>2</sub>O.

5. Trigger-pressure time product. The area defined by the inspiratory delay time and inspiratory trigger pressure, illustrated as Area 1 in Figure 2. The trigger-pressure time product represents the amount of patient effort expended in activating a breath. Ideally, the trigger-pressure time product should be zero.

6. Inspiratory positive pressure area. The area defined by the inspiratory pressure curve beginning with the return of pressure to baseline (after inspiratory delay time) and

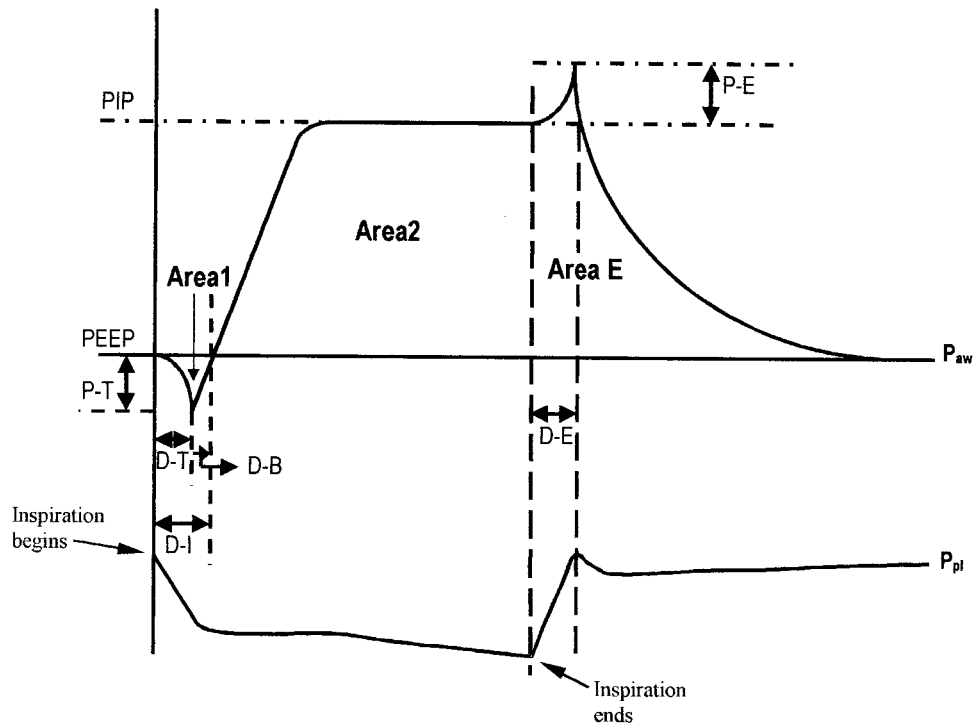


Fig. 2. Schematic illustrating the variables evaluated. See text for definitions of variables.  $P_{aw}$  = peak airway pressure.  $P_{pl}$  = pleural pressure. PIP = peak inspiratory pressure. PEEP = positive end-expiratory pressure.

ending at the time pleural pressure indicated the onset of expiration (Area 2 in Fig. 2). Area 2 represents the ability of the ventilator to pressurize the system: the actual area of pressure-versus-time applied during each inspiration.

7. Inspiratory area percent. The percentage that the remainder of Area 2 minus Area 1 represents of the area of an ideal airway pressure curve, not shown in Fig. 2, calculated as:

$$\text{Area I\%} = \frac{[\text{Area 2} - \text{Area 1}]}{[(\text{PIP} - \text{PEEP}) \times (\text{Inspiratory time})]} \times 100 \quad (1)$$

wherein PIP is peak inspiratory pressure. The ideal airway pressure curve is the rectangle defined by the onset of inspiration (pleural pressure change) vertically to peak pressure extending to the time inspiration ends (pleural pressure change). This calculation is based on our assumption that the most ideal positive pressure breath would immediately pressurize the system on initiation of inspiration and immediately return to baseline at the end of inspiration. Thus, no Area 1 should be present. Optimal performance would be an Area I% of 100%. That is, the closer the ventilation is to that level, the more optimal is its operation, under our assumptions.

8. Peak flow. The maximum ventilator-delivered flow (in L/min) obtained during the inspiratory phase.

The following expiratory variables were measured:

1. Expiratory time delay. The time between the onset of exhalation and the moment when airway pressure falls below the end-inspiratory value. This represents the amount of time it takes for the airway pressure to decrease below set inspiratory level after the lung model begins to expire. Ideally, the expiratory time delay should be zero.

2. Supra-plateau expiratory pressure change. The difference between the maximum pressure during exhalation and the end-inspiratory pressure. This represents the amount of pressure above set inspiratory level that was obtained during the transition to exhalation. Whenever this is present, it indicates that the lung model began to expire before the ventilator started exhalation. Ideally, the supra-plateau expiratory pressure change should be zero.

3. Expiratory pressure area (Area E). The area of the airway pressure curve during expiration, calculated as:

$$\text{Area E} = \int (P_{aw} - \text{PEEP}) dt \text{ (during expiration)} \quad (2)$$

This area represents both the ability of the ventilator to coordinate with the lung model the transition to exhalation and the overall resistance of the expiratory system. Ideally, Area E should be zero.

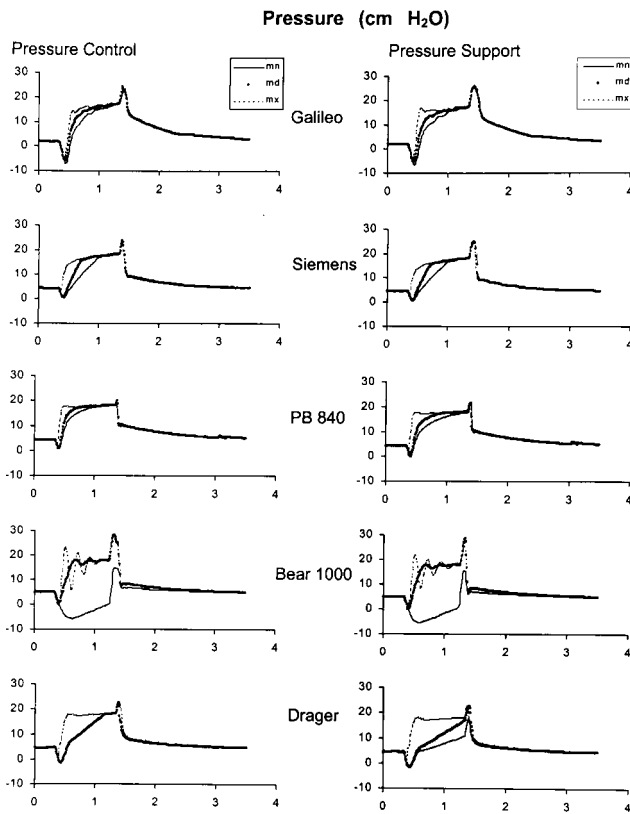


Fig. 3. Airway-pressure-versus-time waveforms for studied ventilators at minimum (mn, continuous line), medium (md, dotted line), and maximum (mx, dashed line) inspiratory rise times in pressure assist/control mode (left column) and pressure support mode (right column). With the BEAR 1000 note the rate of pressurization overshoot of the set level at maximum inspiratory rise time, whereas the rate of pressurization was unable to reach the preset pressure at the minimum inspiratory rise time. PB 840 = Puritan Bennett 840 ventilator.

**Statistics**

Data are expressed as mean ± standard deviation. Comparisons were done using analysis of variance. When significant differences were observed, post hoc analysis was performed with the Scheffé test. Differences were considered significant when  $p < 0.05$ . Because the lung model delivers very consistent breaths and, as a result, small standard deviations, very small differences (frequently within measurement error) were statistically significant. We did not consider differences clinically important unless they were more than 10%. All statistical analysis was performed using commercially available software (SPSS 9.0, SPSS, Chicago, Illinois).

**Results**

**Inspiratory Rise Time**

**Comparison of Pressure Support and Pressure Assist/Control.** Figures 3 and 4 present airway-pressure-ver-

sus-time and flow-versus-time waveforms for each ventilator evaluated, at all 3 rise time settings. There were significant ( $p < 0.05$ ) differences between PS and PA/C modes during inspiration, but few were considered important ( $> 10\%$  difference). Specifically, time to return trigger pressure to baseline, inspiratory delay time, trigger-pressure time product, and Area I% differed  $> 10\%$  between PS and PA/C with the Dräger at the minimum rise time setting (Tables 3 and 4, Figures 5 and 6), and Area I% with the Dräger differed  $> 10\%$  between PS and PA/C at the medium rise time setting. Trigger-pressure time product differed  $> 10\%$  between PS and PA/C on the Galileo at minimum, medium, and maximum, and on the PB 840 at minimum rise time settings. However, significant and important differences were noted during expiration. At most rise time settings, Area E, supra-plateau expiratory pressure change, and expiratory time delay were greater

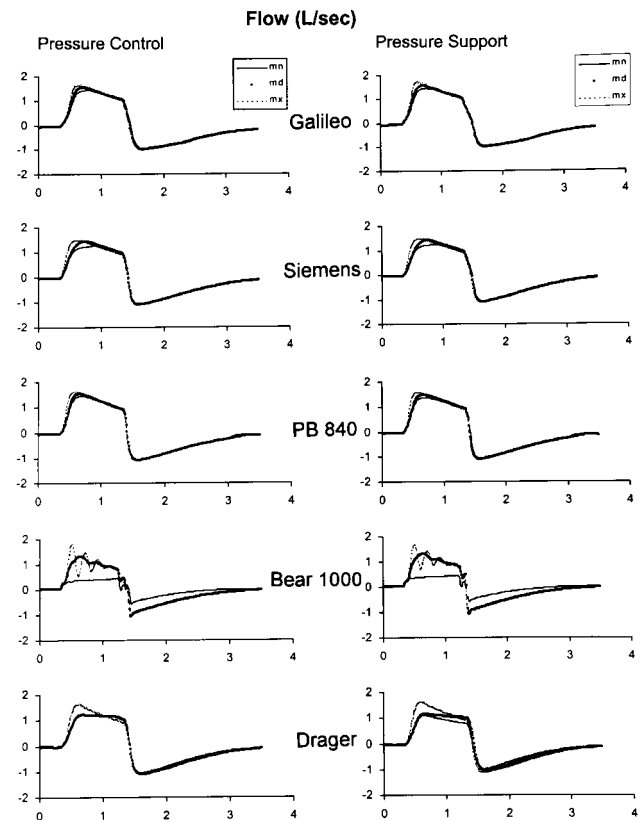


Fig. 4. Flow-versus-time waveforms of studied ventilators at minimum (mn, continuous line), medium (md, dotted line), and maximum (mx, dashed line) inspiratory rise time in pressure assist/control mode (left column) and pressure support mode (right column). With the BEAR 1000 note the rate of pressurization overshoot of the set level at maximum inspiratory rise time, whereas the rate of pressurization was unable to reach the preset pressure at minimum inspiratory rise time. PB 840 = Puritan Bennett 840 ventilator.

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Table 3. Inspiratory Trigger Variables and Area E During Pressure Support at 3 Rise Time Settings

	PS	Galileo	Siemens	PB 840	BEAR 1000*	Dräger
P-T (cm H <sub>2</sub> O)	minimum†	8.42 ± 0.10‡§	4.16 ± 0.10§	4.59 ± 0.17‡§	—	6.61 ± 0.09‡§
	medium†	7.54 ± 0.00§	3.83 ± 0.20§	3.77 ± 0.17§	4.78 ± 0.20	6.28 ± 0.09§
	maximum†	5.69 ± 0.34‡	1.91 ± 0.09‡	1.86 ± 0.25‡	4.43 ± 0.20	4.26 ± 0.00‡
D-T (s)	minimum†	0.12 ± 0.01‡§	0.11 ± 0.01§	0.09 ± 0.01§	—	0.12 ± 0.00‡§
	medium†	0.11 ± 0.00§	0.10 ± 0.01§	0.08 ± 0.01§	0.08 ± 0.01	0.11 ± 0.00§
	maximum†	0.09 ± 0.01‡	0.05 ± 0.01‡	0.06 ± 0.01‡	0.07 ± 0.00	0.07 ± 0.01‡
D-B (s)	minimum†	0.09 ± 0.00‡§	0.11 ± 0.00‡§	0.07 ± 0.01‡§	—	0.16 ± 0.01‡§
	medium†	0.07 ± 0.00§	0.07 ± 0.01§	0.05 ± 0.01§	0.08 ± 0.01§	0.13 ± 0.01§
	maximum†	0.05 ± 0.01‡	0.02 ± 0.00‡	0.02 ± 0.01‡	0.04 ± 0.00‡	0.03 ± 0.01‡
D-I (s)	minimum†	0.21 ± 0.01‡§	0.22 ± 0.01‡§	0.16 ± 0.01‡§	—	0.28 ± 0.01‡§
	medium†	0.18 ± 0.00§	0.17 ± 0.00§	0.13 ± 0.00§	0.15 ± 0.01§	0.24 ± 0.01§
	maximum†	0.13 ± 0.01‡	0.07 ± 0.01‡	0.08 ± 0.00‡	0.11 ± 0.00‡	0.09 ± 0.01‡
Area E (cm H <sub>2</sub> O · s)	minimum†	12.61 ± 0.14	5.87 ± 0.26	6.19 ± 0.04§	—	2.95 ± 0.18‡§
	medium†	12.58 ± 0.11	5.88 ± 0.30	6.27 ± 0.07§	4.59 ± 0.06§	4.58 ± 0.40
	maximum†	12.56 ± 0.06	6.07 ± 0.10	6.51 ± 0.05‡	4.24 ± 0.18‡	4.59 ± 0.06

PS = pressure support.

PB = Puritan Bennett.

\*No data available for BEAR 1000 at minimum setting.

P-T = trigger pressure.

†p < 0.05 among ventilators.

‡p < 0.05 vs medium for specific ventilator.

§p < 0.05 vs maximum for specific ventilator.

||p < 0.05 vs minimum for specific ventilator.

D-T = inspiratory trigger time.

D-B = time to return trigger pressure to baseline.

D-I = inspiratory delay time.

Area-E = area of the airway pressure curve during exhalation.

(p < 0.05 and > 10% difference) during PS (Tables 3 and 4, Figures 7 through 9) than during PA/C.

**Comparison of Rise Times (minimum vs medium vs maximum).** There were significant (p < 0.001) and important (> 10%) differences in inspiratory trigger pressure, inspiratory trigger time, time to return trigger pressure to baseline, inspiratory delay time, and trigger-pressure time product in all ventilators, but only minor differences in Area E, supra-plateau expiratory pressure change, and expiratory time delay (p < 0.05) on some ventilators during both PS and PA/C as rise time was altered (Tables 3 and 4, Figs. 5–9). Peak flow varied (p < 0.05) in all ventilators. With the BEAR and Dräger ventilators, peak flow changed > 10% as rise time varied. At the minimum rise time, only peak flow of the BEAR 1000 could be derived from the waveform, increasing 66% when rise time was changed to medium. As noted in Figure 3, at the minimum rise time setting on the BEAR 1000, airway pressure never exceeded zero, preventing us from measuring the defined variables.

**Comparison Among Ventilators.** There were significant (p < 0.05) and important (> 10%) differences among ventilators at each rise time setting for all variables evaluated. The trigger pressure of the Galileo was greater (p < 0.05) than all other ventilators, and the Siemens trigger pressure

was less (p < 0.05) than all other ventilators except the PB 840. The inspiratory trigger time of the Galileo was greater than all other ventilators except the Dräger, while the PB 840 and BEAR 1000 had the shortest (p < 0.05) inspiratory trigger times. The Galileo had the greatest (p < 0.05) trigger-pressure time product, whereas the trigger-pressure time product of the PB 840 was less (p < 0.001) than the Galileo and Dräger but not less than the Siemens and BEAR. The Area I% of the PB 840 was greater (p < 0.05) than all ventilators except the BEAR. The Area I% of the Galileo was less than all ventilators except the Siemens. The peak flow of the Dräger was less (p < 0.001) than all ventilators except the Siemens. However, the peak flow of the BEAR at minimum was less (p < 0.001) than all ventilators. Area E of the Dräger was less (p < 0.001) than that of all other ventilators. The supra-plateau expiratory pressure change of the PB 840 was less (p < 0.001) than that of all other ventilators. The supra-plateau expiratory pressure change of the BEAR was greater (p < 0.05) at medium and maximum rise times than any other ventilator, whereas at minimum rise time the Galileo had the greatest supra-plateau expiratory pressure change (p < 0.05). The expiratory time delay of the PB 840 was lower (p < 0.001) than that of any other ventilator. In PS mode the expiratory time delay of the Galileo was greater (p < 0.001) than any other ventilator. In PA/C mode the

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Table 4. Inspiratory Trigger Variables and Area E During Pressure Assist/Control at 3 Rise Time Settings

	PS	Galileo	Siemens	PB 840	Bear 1000*	Dräger
P-T (cm H <sub>2</sub> O)	minimum†	9.07 ± 0.25‡§	4.15 ± 0.25§	4.05 ± 0.38§	—	6.28 ± 0.09§
	medium†	7.93 ± 0.25§	3.77 ± 0.17§	3.94 ± 0.17§	4.69 ± 0.38	6.12 ± 0.09§
	maximum†	6.45 ± 0.09‡	1.97 ± 0.28‡	2.08 ± 0.09‡	4.65 ± 0.53	4.48 ± 0.41‡
D-T (s)	minimum†	0.12 ± 0.01§	0.10 ± 0.01‡§	0.09 ± 0.00§	—	0.11 ± 0.01§
	medium†	0.11 ± 0.01§	0.09 ± 0.00§	0.08 ± 0.01§	0.07 ± 0.01	0.12 ± 0.01§
	maximum†	0.10 ± 0.00‡	0.05 ± 0.01‡	0.06 ± 0.01‡	0.08 ± 0.01	0.07 ± 0.00‡
D-B (s)	minimum†	0.09 ± 0.01‡§	0.11 ± 0.01‡§	0.05 ± 0.00‡§	—	0.11 ± 0.01§
	medium†	0.07 ± 0.00§	0.07 ± 0.01§	0.04 ± 0.00§	0.08 ± 0.01§	0.11 ± 0.01§
	maximum†	0.05 ± 0.00‡	0.02 ± 0.01‡	0.02 ± 0.00‡	0.04 ± 0.00‡	0.03 ± 0.01‡
D-I (s)	minimum†	0.22 ± 0.01‡§	0.22 ± 0.01‡§	0.14 ± 0.00‡§	—	0.22 ± 0.01§
	medium†	0.18 ± 0.01§	0.16 ± 0.01§	0.12 ± 0.01§	0.15 ± 0.01§	0.22 ± 0.01§
	maximum†	0.15 ± 0.00‡	0.07 ± 0.00‡	0.08 ± 0.01‡	0.12 ± 0.01‡	0.10 ± 0.01‡
Area E (cm H <sub>2</sub> O · s)	minimum†	10.97 ± 0.31	5.12 ± 0.16	5.94 ± 0.04	—	4.07 ± 0.05§
	medium†	11.36 ± 0.36	5.37 ± 0.41	6.17 ± 0.10	5.82 ± 0.21	4.00 ± 0.04§
	maximum†	11.47 ± 0.14	5.50 ± 0.21	6.03 ± 0.35	5.92 ± 0.26	4.97 ± 0.05‡

PS = pressure support.

PB = Puritan Bennett.

\*No data available for BEAR 1000 at minimum setting.

P-T = trigger pressure.

†p < 0.05 among ventilators.

‡p < 0.05 vs medium for specific ventilator.

§p < 0.05 vs maximum for specific ventilator.

||p < 0.05 vs minimum for specific ventilator.

D-T = inspiratory trigger time.

D-B = time to return trigger pressure to baseline.

D-I = inspiratory delay time.

Area-E = area of the airway pressure curve during exhalation.

expiratory time delay of the BEAR was greater ( $p < 0.05$ ) than that of any other ventilator.

### Inspiration Termination Criteria

Figure 10 illustrates the airway-pressure-versus-time and flow-versus-time waveforms of the Galileo and PB 840

during the 3 inspiration termination criteria settings in PS mode. There were significant ( $p < 0.001$ ) and important ( $> 10\%$ ) differences between all studied expiratory variables among ventilators at each inspiration termination criteria setting (Fig. 11). There were no significant differences among the inspiratory phase variables of each ventilator when the inspiration termination criteria were

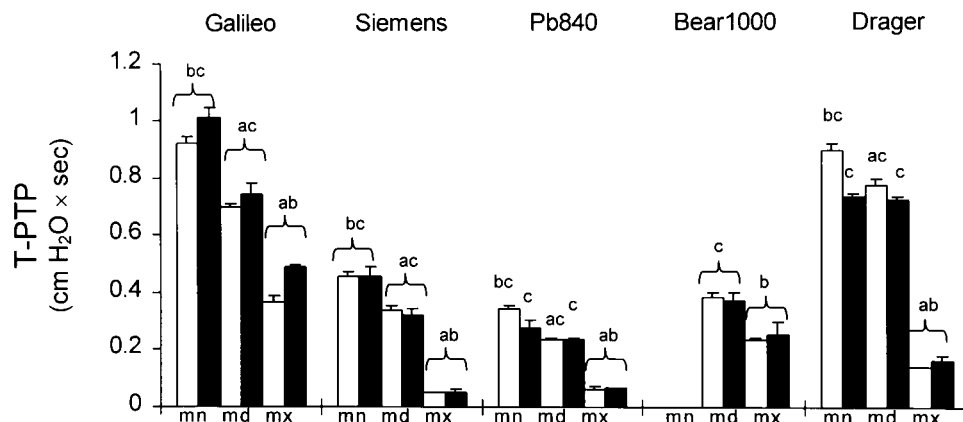


Fig. 5. Effect of minimum (mn), medium (md) and maximum (mx) inspiratory rise times on trigger-pressure time product (T-PTP) during pressure support mode (open bars) and pressure assist/control mode (closed bars) with each tested ventilator. Pb840 = Puritan Bennett 840 ventilator. a:  $p < 0.05$  versus minimum. b:  $p < 0.05$  versus medium. c:  $p < 0.05$  versus maximum. T-PTP decreased with all ventilators in both pressure support and pressure assist/control mode as rise time increased ( $p < 0.005$ ).

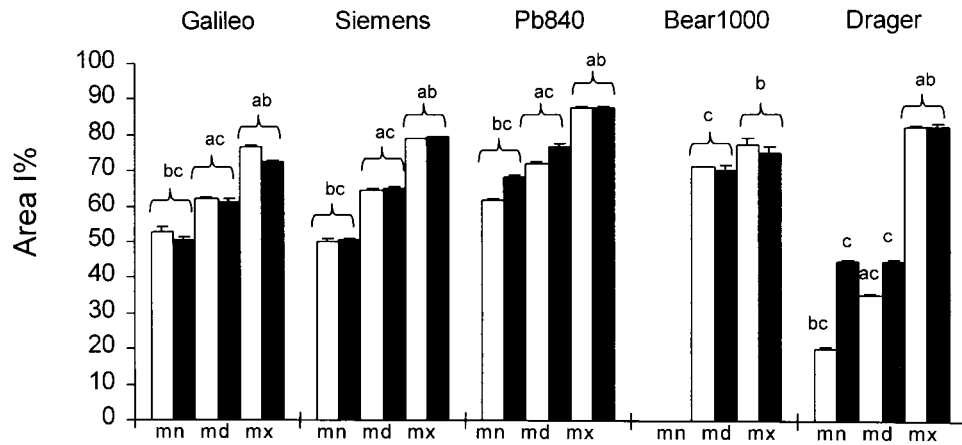


Fig. 6. Effect of minimum (mn), medium (md) and maximum (mx) inspiratory rise times on inspiratory area percent (Area I%) during pressure support mode (open bars) and pressure assist/control mode (closed bars) with each tested ventilator. Pb840 = Puritan Bennett 840 ventilator. a:  $p < 0.05$  versus minimum. b:  $p < 0.05$  versus medium. c:  $p < 0.05$  versus maximum. Area I% increased with all ventilators in both pressure support and pressure assist/control as rise time increased ( $p < 0.05$ ).

changed (Table 5). When the PB 840 was set at the minimum inspiration termination criteria, the ventilator prematurely cycled to exhalation (Fig. 10), and as a result Area E was negative. Consequently, supra-plateau expiratory pressure change and expiratory time delay were zero and they differed significantly ( $p < 0.05$ ) from the medium and maximum settings (Fig. 11).

**Discussion**

The principle findings of this study are:

1. On all ventilators, varying the rise time produced major differences in inspiratory variables, but only small differences in expiratory variables.

2. Changing the inspiration termination criteria did not affect inspiratory variables but markedly affected all expiratory variables evaluated.

3. There were major ( $> 10\%$ ) differences among ventilators as inspiratory rise time and inspiration termination criteria were varied.

4. There were minimal differences between PS and PA/C on most ventilators as inspiratory rise time was altered.

**Rise Time**

It has been clearly established that patient effort and work of breathing are affected by the ventilator's ability to meet patient peak inspiratory demand.<sup>12,13</sup> If flow does not match patient demand, patient-ventilator dyssynchrony

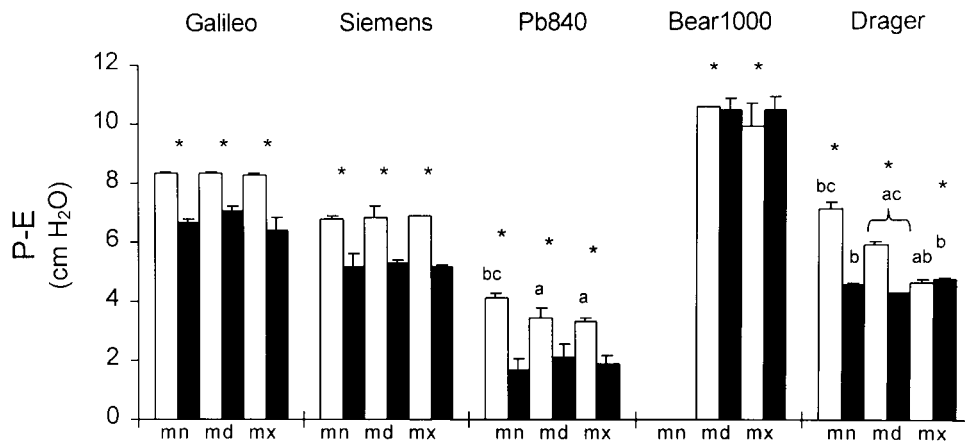


Fig. 7. Effect of minimum (mn), medium (md), and maximum (mx) inspiratory rise times on supra-plateau expiratory pressure change (P-E) during pressure support mode (open bars) and pressure assist/control mode (closed bars) with each tested ventilator. Pb840 = Puritan Bennett 840 ventilator. a:  $p < 0.05$  versus minimum. b:  $p < 0.05$  versus medium. c:  $p < 0.05$  versus maximum. \*  $p < 0.05$  for pressure support versus pressure assist/control.

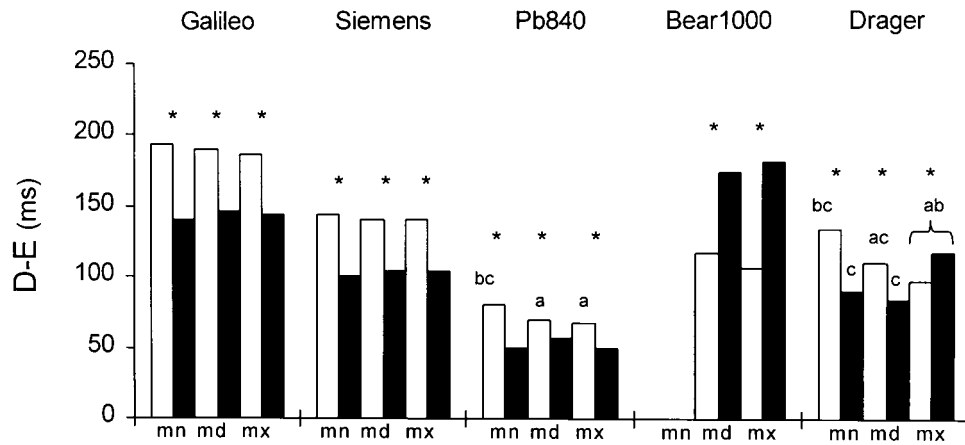


Fig. 8. Effect of minimum (mn), medium (md), and maximum (mx) inspiratory rise times on expiratory time delay (D-E) during pressure support mode (open bars) and pressure assist/control mode (closed bars) with each tested ventilator. Pb840 = Puritan Bennett 840 ventilator. a:  $p < 0.05$  versus minimum. b:  $p < 0.05$  versus medium. c:  $p < 0.05$  versus maximum. \*  $p < 0.05$  for pressure support versus pressure assist/control.

occurs.<sup>1,6</sup> In general, PS and PA/C are better capable of meeting inspiratory demand than is volume ventilation.<sup>1,2</sup> Ideally, in pressure ventilation, the rise in gas flow should match the patient's demand for flow.<sup>5</sup> Although studies of flow synchrony during pressure ventilation suggest that many patients, because of increased ventilatory demand, require a rapid rise time, there are patients in whom a rapid rise time results in the initial system pressure exceeding the set level.<sup>14-16</sup> In these patients a lower rise time is preferable.

All the ventilators we tested had a large range in the levels of inspiratory variables evaluated as rise time was altered. However, the range was not linear in most ventilators. The greatest change occurred when moving from

medium to maximum rise time. This was not true for the BEAR, which performed poorly at minimum setting, primarily because of limited peak flow. We did not expect a change in trigger pressure as rise time was varied but did expect an increase in the time to return trigger pressure to baseline, total time delay, and trigger-pressure time product. The increase in trigger pressure as rise time decreased at a fixed lung model ventilatory drive is a result of the inability of the flow provided by the ventilator to reverse the descent in airway pressure as quickly as at a more rapid rise time. That is, activation of the flow demand system was less capable of reversing the descent in airway pressure as rise time decreased.

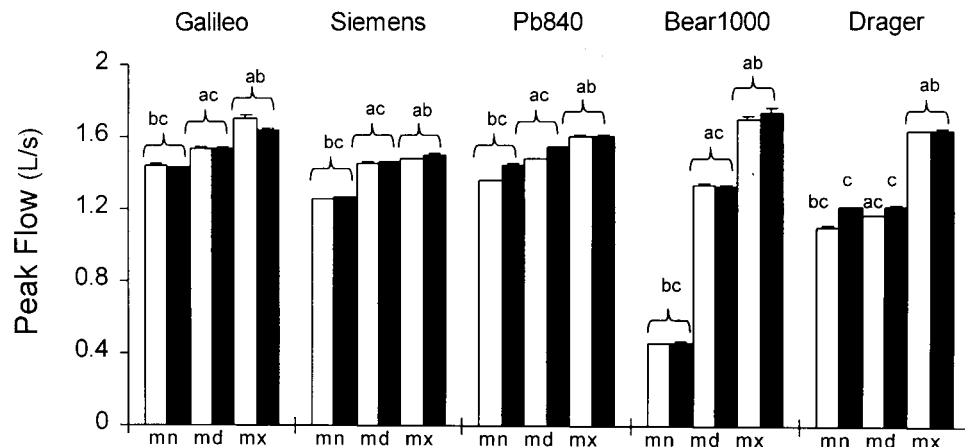


Fig. 9. Effect of minimum (mn), medium (md) and maximum (mx) inspiratory rise times on peak flow during pressure support mode (open bars) and pressure assist/control mode (closed bars) with each tested ventilator. a:  $p < 0.05$  versus minimum. b:  $p < 0.05$  versus medium. c:  $p < 0.05$  versus maximum. Peak flow increased with all ventilators in both pressure support and pressure assist/control as rise time increased ( $p < 0.05$ ).

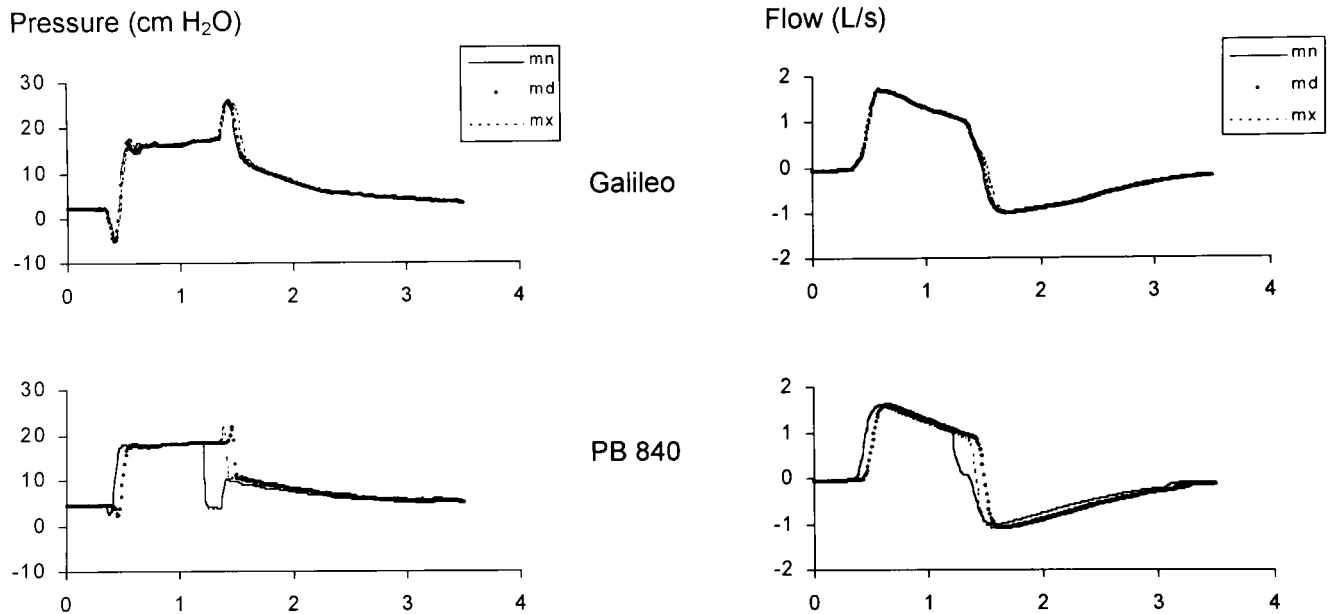


Fig. 10. Airway-pressure-versus-time (left column) and flow-versus-time (right column) waveforms of studied ventilators at minimum (mn, continuous line), medium (md, dotted line), and maximum (mx, dashed line) inspiration termination criteria. Premature exhalation occurred when minimum inspiration termination criteria were set on the Puritan Bennett 840 ventilator (PB 840).

On some of these ventilators (PB 840, Siemens 300, and Galileo), little change in peak flow was observed as rise time decreased. This is a result of 2 factors: (1) the consistent ventilatory pattern of the lung model unaffected by changes made on the ventilator (contrary to what is observed in patients), and (2) the capability of these ventilators to maintain gas delivery in spite of a change in rise time. As noted in Figures 3 and 4, airway pressure and flow waveforms changed, but peak flow changed little between minimum and maximum rise time settings.

In this evaluation, changes in rise time had minimal effect on cycling to exhalation. This is contrary to what we expected, particularly in ventilators that use a fixed percentage of peak flow as the first criterion for termination of inspiration. We anticipated, as shown by Branson et al<sup>14</sup> and Bonmarchard et al,<sup>16</sup> that as rise time was decreased, peak flow would decrease and inspiratory time would increase. However, our lung model had a fixed inspiratory time of 1 second and a fixed ventilatory drive, so expected changes in expiratory variables may not have been observable. In fact, the lung model end-inspiratory flow was high, resulting in all ventilators cycling to exhalation by pressure criteria. Our results have evaluated the ability of these ventilators to cycle when patient end-inspiratory flow exceeds the ventilator's termination criteria.

### Inspiration Termination Criteria

Inspiration in PS mode is terminated by one of 3 mechanisms. The primary method is a decrease in flow. The

second is a rise in pressure above the target setting. The third is inspiratory time exceeding a specific maximum duration. It has been shown by Jubran et al<sup>9</sup> and Parthasarathy et al<sup>17</sup> that cycle dyssynchrony during PS mode occurs because of activation of abdominal muscles during the inspiratory phase, increasing patient effort and the number of failed trigger efforts, whereas variability in inspiratory cycling criteria has been shown by MacIntyre and Ho<sup>15</sup> to have limited impact on patient-ventilator synchrony. However, Calderini et al<sup>18</sup> showed marked improvement in patient ventilator synchrony during noninvasive ventilation when a fixed inspiratory time during PA/C mode replaced the variable inspiratory time in PS mode.

Recently, Yamada and Du<sup>19</sup> mathematically modeled the factors that affect synchrony during the transition from inspiration to expiration. Specifically, they determined that the relationship of flow at the end of a patient's neural inspiratory time to peak inspiratory flow is related to 2 factors: (1) the ratio of the respiratory time constant to the patient's neural inspiratory time, and (2) the ratio of the set PS level to the maximum inspiratory muscle pressure. As a result, they reported that the ratio of patient neural inspiratory time to peak inspiratory flow may range from 1 to 85, dependent on respiratory mechanics and ventilatory drive. Thus, with set inspiration termination criteria, a patient can end inspiration before or after the ventilator reaches its termination flow. Variability in inspiration termination criteria clearly increases the probability of patient-ventilator synchrony. In our experience, problems with

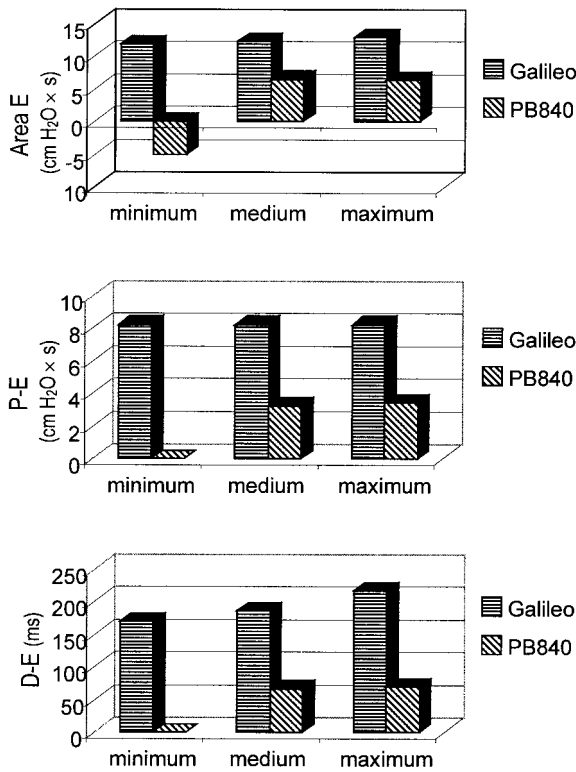


Fig. 11. Effect of inspiration termination criteria on Area E (top panel), supra-plateau expiratory pressure change (P-E) (middle panel), and expiratory time delay (D-E) (bottom panel) in pressure support mode. There were significant ( $p < 0.001$ ) differences in Area E, P-E, and D-E between the Puritan Bennett 840 (PB840) and Galileo at every inspiration termination criteria setting.

inspiration termination synchrony are primarily observed in patients with chronic obstructive pulmonary disease ventilated with ventilators requiring very low fixed flows or very small percentages of peak flow to terminate inspiration.

As shown in Figure 11, there were marked differences between the Galileo and PB 840 in expiratory variables as inspiration termination criteria were varied. The PB 840 had a wide range of terminating flow; so much so that at the maximum setting the ventilator terminated inspiration before the lung model was ready to exhale, which is potentially a concern in patients who require careful observation of waveforms and ventilatory response to alterations in the termination criteria. On the other hand, changes to the termination criteria on the Galileo did not seem to affect the ventilator's cycling to exhalation. We have no specific explanation for that failure. No changes were made in the lung model setting between ventilators. Since the range of variability in termination criteria is similar between these 2 ventilators (see Table 2) and the peak flow delivered by these 2 ventilators differed by  $< 10\%$  during this evaluation (see Table 5), we expected the Galileo and PB 840 to respond similarly.

**Automation**

As we have shown, all of the ventilators studied have the ability to vary rise time or both rise time and inspiration termination criteria. However, clinicians often have difficulty finding the proper settings for these variables. Proper setting of both requires careful assessment of patient synchrony with the ventilator, which is difficult to achieve without observation of the inspiratory airway pressure waveform. Ideally set rise time avoids a delay in initial gas delivery and a concavity of the initial rise in pressure (inadequate rise time) and also avoids pressure overshooting the target pressure in early inspiration (too high a rise time). Proper setting of inspiration termination criteria avoids an increase in airway pressure at end inspiration (neural inspiratory time shorter than ventilator inspiratory time). However, even if we can adjust these variables perfectly, the settings may only be perfect for the moment they are set. Any change in patient demand or neural inspiratory time will result in dyssynchrony, as in volume ventilation with a fixed inspiratory flow pattern. A

Table 5. Inspiratory Trigger Variables, Area I%, and Peak Flow During Pressure Support at 3 Inspiration Termination Criteria Settings

	ITC	Galileo	PB 840
P-T (cm H <sub>2</sub> O)	minimum*	6.83 ± 0.25	2.19 ± 0.10
	medium*	6.83 ± 0.25	2.03 ± 0.25
	maximum*	6.61 ± 0.25	2.35 ± 0.41
D-T (s)	minimum*	0.09 ± 0.01	0.06 ± 0.01
	medium*	0.10 ± 0.01	0.06 ± 0.01
	maximum*	0.09 ± 0.01	0.06 ± 0.00
D-B (s)	minimum*	0.05 ± 0.01	0.02 ± 0.01
	medium*	0.05 ± 0.00	0.02 ± 0.01
	maximum*	0.05 ± 0.00	0.02 ± 0.00
D-I (s)	minimum*	0.14 ± 0.00	0.08 ± 0.01
	medium*	0.15 ± 0.01	0.08 ± 0.00
	maximum*	0.14 ± 0.01	0.08 ± 0.00
T-PTP (cm H <sub>2</sub> O · s)	minimum*	0.47 ± 0.02	0.07 ± 0.00
	medium*	0.48 ± 0.03	0.07 ± 0.01
	maximum*	0.45 ± 0.02	0.08 ± 0.02
Area I%	minimum*	75.43 ± 0.45	85.37 ± 1.44
	medium*	74.86 ± 1.45	86.75 ± 0.58
	maximum*	74.94 ± 0.85	86.42 ± 0.57
Peak flow (L/min)	minimum*	1.71 ± 0.03	1.60 ± 0.01
	medium*	1.71 ± 0.03	1.60 ± 0.00
	maximum*	1.70 ± 0.02	1.60 ± 0.00

ITC = inspiration termination criteria.  
 PB = Puritan Bennett.  
 P-T = trigger pressure.  
 D-T = inspiratory trigger time.  
 D-B = time to return trigger pressure to baseline.  
 D-I = inspiratory delay time.  
 T-PTP = trigger pressure time product.  
 Area I% = inspiratory area percent.  
 \* $p < 0.05$  among ventilators.

patient's need for a specific rise time and inspiration termination criteria can vary rapidly, making it necessary to reset these variables. The ability for clinicians to adjust rise time and inspiration termination criteria is an improvement over the original design of pressure-targeted ventilation, but it may not be the final improvement. As illustrated by many investigators, there are many issues associated with dyssynchrony during pressure ventilation.<sup>5-7,9,14-19</sup> The next step is to automate the adjustment of rise time and inspiration termination criteria to ensure continued synchrony. We would expect the next generation of mechanical ventilators to be able to assess patient synchrony during pressure ventilation and to automatically adjust rise time and inspiration termination criteria on a breath-by-breath basis.<sup>19</sup>

### Pressure Support Versus Pressure Assist/Control

Little difference exists between the operation of PS and PA/C as rise time is adjusted with any of the ventilators we evaluated. This is consistent with our previously published data comparing these 2 pressure-targeted modes on these same ventilators.<sup>11</sup>

### Limitations

There are a number of limitations to this study. Most importantly, it was performed on a lung model. As a result, extrapolating the data to patients must be done cautiously, since spontaneously breathing patients have numerous inputs controlling ventilation (neural, mechanical, and chemical, as well as pain and anxiety). Second, the lung model had a fixed inspiratory time of 1.0 s. Our results may have been different if inspiratory time was different. Third, we evaluated only a single lung model peak inspiratory flow. The performance of these ventilators may differ at other peak inspiratory flows. Finally, the large differences observed in this lung model study may not reflect any variation in clinical impact with the use of these ventilators. Clinical studies are needed to identify the actual clinical impact of changes in rise time or inspiration termination criteria with any ventilator.

### Conclusions

Varying the rise time settings resulted in major differences in inspiratory variables on all ventilators evaluated, but little difference in expiratory variables. The opposite occurred as inspiration termination criteria were altered. Marked changes in expiratory variables were observed, but little effect was observed on inspiratory variables. Only small (but statistically significant) differences were observed on any ventilator between PS and PA/C, but large differences were observed between ventilators during all conditions evaluated. The differences between PS and PA/C were mostly related to variables associated with expiration.

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