Anesthesiology 2002; 96:162–72

Continuous Positive Airway Pressure in New-generation Mechanical Ventilators

A Lung Model Study

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Background: **A number of new microprocessor-controlled mechanical ventilators have become available over the last few years. However, the ability of these ventilators to provide continuous positive airway pressure without imposing or performing work has never been evaluated.**

Methods: **In a spontaneously breathing lung model, the authors evaluated the Bear 1000, Drager Evita 4, Hamilton Galileo, Nellcor-Puritan-Bennett 740 and 840, Siemens Servo 300A, and Bird Products Tbird AVS at 10 cm H_2O continuous positive airway pressure. Lung model compliance was 50 ml/cm H_2O with a resistance of 8.2 cm $H_2O \cdot l^{-1} \cdot s^{-1}$, and inspiratory time was set at 1.0 s with peak inspiratory flows of 40, 60, and 80 l/min. In ventilators with both pressure and flow triggering, the response of each was evaluated.**

Results: **With all ventilators, peak inspiratory flow, lung model tidal volume, and range of pressure change (below baseline to above baseline) increased as peak flow increased. Inspiratory trigger delay time, inspiratory cycle delay time, expiratory pressure time product, and total area of pressure change were not affected by peak flow, whereas pressure change to trigger inspiration, inspiratory pressure time product, and trigger pressure time product were affected by peak flow on some ventilators. There were significant differences among ventilators on all variables evaluated, but there was little difference between pressure and flow triggering in most variables on individual ventilators except for pressure to trigger. Pressure to trigger was 3.74 ± 1.89 cm H_2O (mean ± SD) in flow triggering and 4.48 ± 1.67 cm H_2O in pressure triggering ($P < 0.01$) across all ventilators.**

Conclusions: **Most ventilators evaluated only imposed a small effort to trigger, but most also provided low-level pressure support and imposed an expiratory workload. Pressure triggering during continuous positive airway pressure does require a slightly greater pressure than flow triggering.**

THE ability of mechanical ventilators to provide continuous positive airway pressure (CPAP) without imposing or performing work on patients has been questioned by many investigators.[1–5] Early generations of mechanical ventilators imposed high levels of inspiratory effort during CPAP triggering.[6–8] More recent generations of ventilators have minimized imposed effort by more responsive demand systems and more aggressive flow delivery algorithms.[9–13] However, the result has been the application of a low level of pressure support during CPAP breathing.[12,13]

As a result of these concerns, there has been much debate over the use of mechanical ventilators during spontaneous breathing trials.[14,15] The mechanical ventilator does have advantages over a simple T piece for the evaluation of spontaneous breathing capability. The ventilator can provide continuous monitoring of respiratory rate and tidal volume, notification of an abnormal breathing pattern, and is a simple means of providing CPAP to patients already receiving ventilatory support. However, concern over imposed or performed work by the ventilator during a spontaneous breathing trial has lead many clinicians to prefer the T piece for evaluation of spontaneous breathing capabilities.[16–18]

Over the last 20 yr, many manufacturers have introduced flow triggering for ventilator activation. Although controversy exists over the superiority of flow triggering compared with pressure triggering during assisted ventilatory modes,[19–25] most have accepted that during CPAP, flow triggering is more responsive than pressure triggering.[26–29]

Today there are numerous mechanical ventilators available whose function during CPAP has not been evaluated. In four of these ventilators, the option of either pressure or flow triggering is available. Using a spontaneously breathing lung model, we evaluated gas delivery during CPAP in seven of these ventilators and compared pressure to flow triggering in the four units with both triggering options.

Materials and Methods

Lung Model

A bellows-in-a-box lung model was used to simulate spontaneous breathing (fig. 1). The space between the rigid box and the bellows represented the pleural space. The box was connected to a low compliance T tube through which gas flow created negative pressure in the pleural space. Source gas (50 psi, oxygen) was connected to a pressure regulator (SMC AR200, 7–120 psi; SMC Co., Tokyo, Japan) and a proportional solenoid

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Received from the Departments of Anesthesia and Respiratory Care, Massachusetts General Hospital and Harvard Medical School, Boston, Massachusetts. Submitted for publication November 14, 2000. Accepted for publication August 29, 2001. Supported by a grant from the Japanese government, Osaka, Japan (to Dr. Takeuchi); Alliance Pharmaceuticals, San Diego, California; Nelcor Puritan Bennett, Carlsbad, California; Seimens Medical, Danvers, Massachusetts; Drager Medical Products, Telford, Pennsylvania; and INO Therapeutics, Clinton, New Jersey (to Dr. Kacmarek); INO Therapeutics; Nelcor Puritan Bennett; Thermorespiratory Group, Palm Springs, California; Monoghan Medical; and Respironics, Carlsbad, California (to Dr. Hess).

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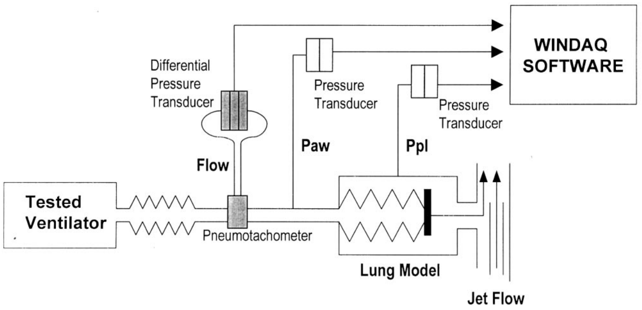

Fig. 1. Illustration of spontaneous breathing lung model. Pao = airway opening pressure; Ppl = intrapleural pressure.

valve (SMC 315; SMC Co.). A function generator (EGC 2230; Kenwood, Tokyo, Japan) controlled the opening of the solenoid valve. Adjustment of the regulator allowed variation of the negative pressure in the pleural space, and the function generator simulated a variety of spontaneous breathing patterns. Thus, inspiratory flow demand, respiratory rate, and inspiratory time were controlled independently. A linear resister (7100 R-5; Hans-Rudolph Inc., Kansas City, MO) created an airway resistance of 8.2 cm $H_2O \cdot l^{-1} \cdot s^{-1}$ at a flow rate of 60 l/min. Compliance of the lung model (50 ml/cm H_2O) was determined by a spring in the bellows.

Ventilators

The following seven ventilators were evaluated: Bear 1000 (Bear Medical Systems, Inc., Riverside, CA), Drager Evita 4 (Drager, Inc., Telford, PA), Hamilton Galileo (Hamilton Medical AG, Rhazuns, Switzerland), Nellcor Puritan-Bennett 740 and 840 (Nellcor Puritan-Bennett Corp., Carlsbad, CA), Siemens Servo 300A (Siemens-Elema AB, Solna, Sweden), and Tbird AVS (Bird Products Corp., Palm Springs, CA). Each ventilator was connected to the lung model using a standard heated wire circuit (Hudson Respiratory Care Inc., Temecula, CA) and a Conchatherm IV Humidifier (Hudson Respiratory Care Inc.). However, the humidifier was not operational during any evaluation. Abbreviations used and settings for each ventilator are summarized in table 1.

Measurement and Calibration

A pneumotachometer (model 3700A; Hans-Rudolph Inc.) was placed at the airway opening of the lung model. The pressure differential across the pneumotachometer was measured (45-14-871 ± 2 cm H_2O; Validyne, Northridge, CA), amplified (model 8805C; Hewlett Packard, Waltham, MA), digitized, and converted to a flow signal using a computerized graphics program (WINDAQ; Dataq Instruments Inc., Akron, OH). The pneumotachometer was calibrated at 1 l/s flow delivered by a precision flowmeter (Brooks Instruments, Hatfield, PA). Pressure at the airway opening and in the simulated pleural space was measured with differential pressure transducers (45-32-871 ± 100 cm H_2O; Validyne). The pressure transducers were calibrated simultaneously at 20 cm H_2O using a water manometer. Pressure signals were amplified (8805 C; Hewlett Packard) and digitized (WINDAQ).

Experimental Protocol

In this study, simulated spontaneous breaths were set as follows: respiratory rate, 12 breaths/min; inspiratory time, 1.0 s; lung model peak inspiratory flow rates before ventilator attachment, 40, 60, and 80 l/min. CPAP was set at 10 cm H_2O in all seven ventilators. Each ventilator was tested at the three lung model peak inspiratory flows. If the ventilator could be set in both flow and pressure triggering, we evaluated both at all peak flows. Inspiratory trigger sensitivity, base flow (or continuous flow) during the expiratory phase, and expiratory trigger sensitivity (cycling criteria) of tested ventilators are listed in table 1. Inspiratory trigger sensitivity was set as sensitive as possible without causing autotriggering in both trigger modes. In EVITA, a fixed pressure trigger sensitivity of −0.2 cm H_2O and base flow of 1 l/min were set by the manufacturer (flow triggering is not active during CPAP in this ventilator). In BEAR and T BIRD, we arbitrarily set base flow at 5 and 10 l/min, respectively. Base flow of GALILEO, PB840, and S300 was predetermined by the manufacturer. In PB740, there was no "constant" base flow even though this is a flow trigger ventilator. In GALILEO and PB840, we set expiratory trigger sensitivity at 25% of peak inspiratory flow rate to be consistent with the settings of other ventilators. Other ventilator's expiratory trigger sensitivity was predetermined by the manufacturer.

Data Acquisition and Analysis

Airway pressure (Pao), intrapleural (between box and bellows) pressure (Ppl), and airway flow were measured. All signals were digitized at 100 Hz and recorded using WINDAQ. The WINDAQ playback software was used to analyze data. We analyzed three consecutive breaths at each inspiratory flow in each ventilator during both triggering modes.

The beginning and the end of the inspiratory phase (inspiratory time: TI) was determined by changes in intrapleural pressure (fig. 2). A negative deflation in pleural pressure indicated the start of the inspiratory phase and the subsequent positive deflection signaled the end of inspiration. Airway baseline pressure (P_{BL}) was defined as airway pressure measured at the end of expiration. From the beginning of inspiration, the time required to decrease airway pressure to the lowest pressure below P_{BL} was recorded as the inspiratory trigger delay time (D_T). Inspiratory trigger pressure (P_T) was defined as the difference between P_{BL} and the lowest pressure below P_{BL} during triggering of inspiration. The airway pressure time product required to trigger ventilation (PTP_T) prebreath was defined as the area of the

Table 1. Abbreviations and Setup of All Ventilators

Ventilator	Abbreviation	Trigger	Inspiratory Sensitivity	Base Flow (l/min)	Expiratory Sensitivity for Flow and Pressure
Bear 1000	BEAR	F	1 l/min	5	30% of PIF
		P	-0.2 cm H_2O	0	
Drager Evita 4	EVITA	P	-0.2 cm H_2O	0	25% of PIF
Hamilton Galileo	GALILEO	F	2 l/min	4	25% of PIF
		P	-2.5 cm H_2O	0	
Nellcor Puritan-Bennett 740	PB740	F	1.3 l/min	0	25% of PIF, 10 l/min, 3 cm H_2O above P_{target}
Nellcor Puritan-Bennett 840	PB840	F	1.5 l/min	3	25% of PIF, 1.5 cm H_2O above P_{target}
		P	-1 cm H_2O	0	
Siemens Servo 300A	S300	F	Green–red line	2	25% of PIF, 8 cm H_2O above P_{target}
		P	-1 cm H_2O	0	
Tbird AVS	T BIRD	F	1 l/min	10	25% of PIF

F = flow triger; P = pressure trigger; PIF = peak inspiratory flow rate; P_{target} = target pressure.

airway pressure–time tracing below P_{BL} during triggering. The airway pressure time product during inspiration (PTP_I) per breath was defined as the area of the airway pressure–time tracing throughout total inspiration

$$PTP_T = \int_0^{D_T} (P_{BL} - Pao)dt;\ \text{during triggering phase} \tag{1}$$

$$PTP_I = \int_0^{T_I} (Pao - P_{BL})dt;\ \text{during inspiratory phase} \tag{2}$$

The ventilator's delivered peak inspiratory flow (VPF) and delivered inspiratory tidal volume (V_T) were also measured.

During the expiratory phase, the expiratory delay time (D_E) was defined as the time from the onset of expiration until airway pressure reached its peak level during the expiratory phase. Expiratory trigger pressure (P_{Emax}) was defined as airway pressure difference between P_{BL} and maximum Pao during exhalation. The airway pressure difference between minimum Pao during triggering and the maximum Pao during exhalation (dP_{AW}) was also calculated. The expiratory airway pressure time product (PTP_E) per breath was defined as the area of the Pao–time tracing above baseline from the onset of expiration to the return of airway pressure to baseline (fig. 2)

$$PTP_E = \int_{T_I}^{5} (Pao - P_{BL})dt;\ \text{during expiratory phase} \tag{3}$$

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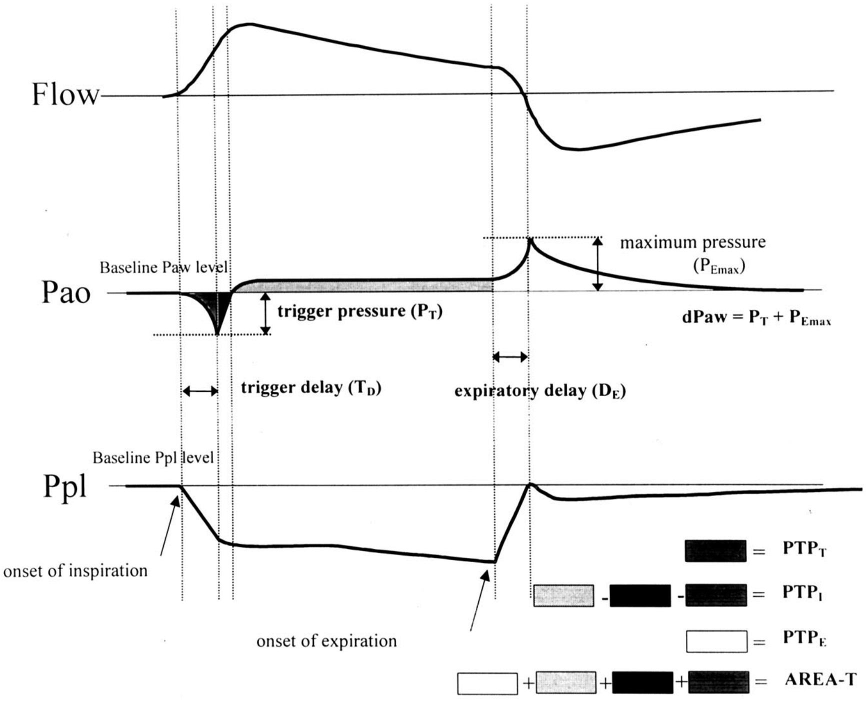

Fig. 2. Illustration of parameters evaluated. Pao = airway opening pressure; Ppl = intrapleural pressure; D_T = inspiratory trigger delay time; P_T = inspiratory trigger pressure; PTP_T = triggering pressure time product; PTP_I = inspiratory pressure time product; P_{Emax} = expiratory trigger pressure; D_E = expiratory delay time; dP_{AW} = maximum airway pressure change; PTP_E = expiratory pressure time product; AREA-T = integration of total pressure fluctuation from P_{BL}.

The integration of total pressure fluctuation from baseline pressure throughout both inspiration and expiration (AREA-T) per breath was calculated as follows:

$$\text{AREA} - \text{T} = \int_{0}^{5} |(\text{Pao} - \text{P}_{\text{BL}})|\text{dt} \qquad (4)$$

Statistical Analysis

Three consecutive breaths were analyzed for each experimental setting after stabilization. All values were reported as mean ± SD. Dependent variables evaluated were D_T, P_T, PTP_T, PTP_I, VPF, V_T, D_E, P_{Emax}, dP_{AW}, PTP_E, and AREA-T. For comparing the effect of ventilators (each trigger mode was considered a different ventilator in this comparison), one-way analysis of variance was performed. For comparing the effect of flow demand, two-way analysis of variance was performed for each ventilator and flow demand. For comparing the effect of triggering mode, two-way analysis of variance was performed for each ventilator and triggering method. *Post hoc* analysis was performed with the Scheffé test if analysis of variance reached significance. Significance was set at $P < 0.05$.

Results

Representative airway pressure waveforms for each ventilator at a peak lung model inspiratory flow of 80 l/min during pressure and flow triggering are shown in figure 3. None of the ventilators mistriggered, nor did any ventilator prematurely cycle to expiration. To simplify the comparison among ventilators, the flow-triggered S300 ventilator was used as a statistical reference for all parameters except dP_{AW} and P_{Emax}, for which the PB840 ventilator was used as a reference.

Difference between Ventilators during Inspiratory Phase

Inspiratory trigger delay time during flow-triggered BEAR, pressure-triggered EVITA, and flow- and pressure-triggered GALILEO were significantly longer than that of flow-triggered S300 (fig. 4A). P_T of the BEAR and GALILEO (both flow and pressure triggering) was significantly larger than that of flow-triggered S300 (fig. 4B). The PTP_T during flow-triggered BEAR, pressure-triggered EVITA, and flow- and pressure-triggered GALILEO was significantly larger than that of flow-triggered S300 (fig. 4C). The PTP_I of the BEAR (both flow and pressure triggering) and pressure-triggered EVITA were negative and significantly smaller than that of flow-triggered S300 (fig. 4D). A negative PTP_I indicates that overall effort was performed by the lung model during the inspiratory phase. A positive PTP_I indicates overall effort was performed by the ventilator. There was no statistical difference in VPF and V_T among ventilators (table 2).

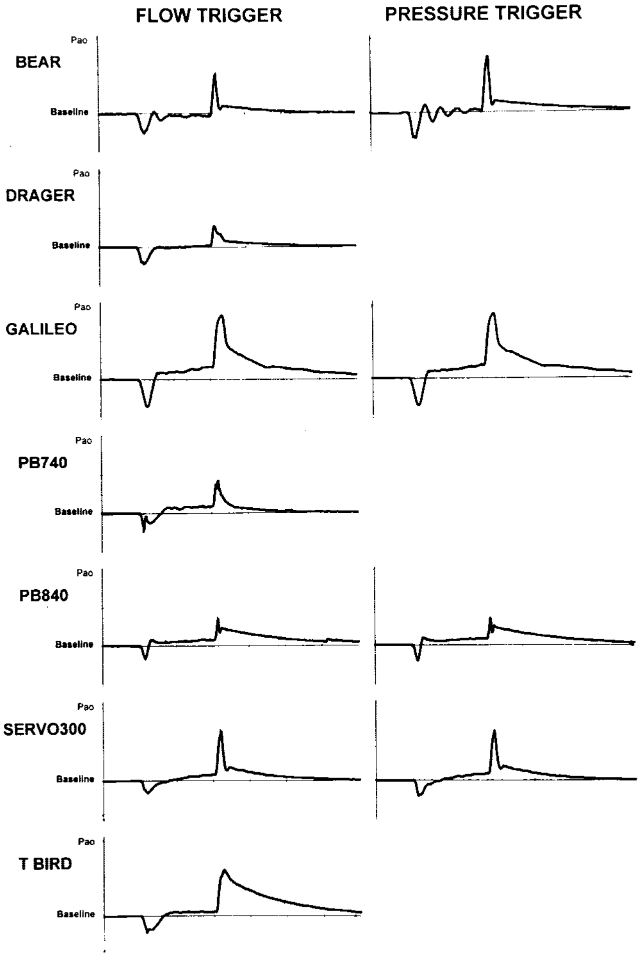

Fig. 3. Airway pressure *versus* time waveforms for all ventilators evaluated at 80 l/min peak flow. Pao = airway opening pressure.

Difference between Ventilators during Expiratory Phase

Expiratory delay time during pressure-triggered EVITA and PB840 (both flow and pressure triggering) were significantly shorter than that of flow-triggered S300 (fig. 5A). On the other hand, D_E during flow-triggered GALILEO was significantly longer than that of flow-triggered S300 (fig. 5A). The PTP_E of the GALILEO (both flow and pressure triggering) and flow-triggered T BIRD were significantly larger than that of flow-triggered S300 (fig. 5B). The dP_{AW} and P_{Emax} of flow-triggered S300 was not different from other ventilators. However, compared with flow-triggered PB840, dP_{AW} during pressure-triggered BEAR and GALILEO (both flow and pressure) were significantly larger (fig. 5C), and P_{Emax} of the GALILEO (both flow and pressure) was significantly larger. The integration of total pressure fluctuation from P_{BL} (AREA-T) of the GALILEO (both flow and pressure trig-

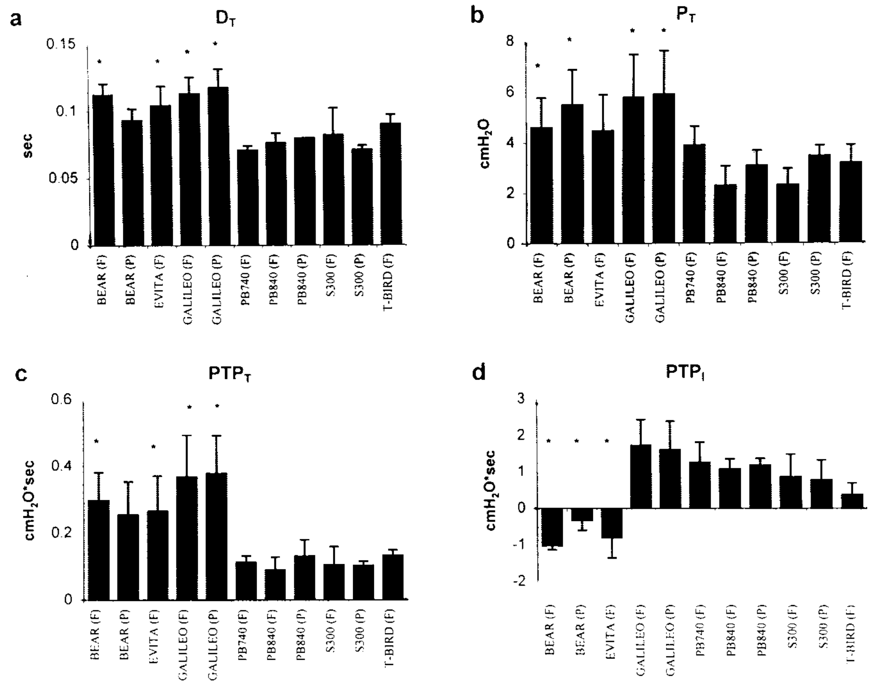

Fig. 4. Inspiratory phase variables evaluated: (*A*) inspiratory trigger delay time (D_T); (*B*) inspiratory trigger pressure (P_T); (*C*) triggering pressure time product (PTP_T); (*D*) inspiratory pressure time product (PTP_I). Mean ± SD of all inspiratory peak flows. *$P < 0.05$ *versus* flow-triggered S300.

gering) and flow-triggered T BIRD were significantly larger than that of flow-triggered S300 (fig. 5D).

Effect of Peak Flow

The effect of varying peak lung model flow on all evaluated variables in each ventilator is shown in tables 2 and 3. VPF, V_T, P_{Emax}, and dP_{AW} increased significantly as flow demand increased in all ventilators. There was almost no significant effect of varying flow on D_T and D_E in any ventilator. P_T and PTP_T of BEAR, EVITA, and GALILEO increased significantly as peak flow increased. PTP_I of EVITA, GALILEO, PB740, and S300 decreased significantly as peak flow increased. PTP_E and AREA-T of T BIRD increased significantly as peak flow increased.

Effect of Triggering Method

The effect of triggering method on all evaluated variables in each ventilator with both triggers is shown in figure 6. There was an interaction between ventilator and triggering method for D_T, PTP_E, and AREA-T. In the BEAR, *post hoc* analysis revealed that PTP_E and AREA-T of flow trigger were significantly smaller than those of pressure trigger (1.59 ± 0.61 *vs.* 3.64 ± 0.99 and 2.73 ± 0.64 *vs.* 4.81 ± 0.90 cm $H_2O \cdot s$; fig. 5). There was no interaction between ventilator and triggering method for P_T, PTP_T, PTP_I, VPF, V_T, D_E, P_{Emax}, and dP_{AW}. Between flow trigger and pressure trigger across all ventilators, only P_T showed a significant difference (3.74 ± 1.89, 4.48 ± 1.67 cm H_2O; fig. 6).

Discussion

The major findings of this study can be summarized as follows: (1) there is a large range of variability among the seven ventilators evaluated during CPAP; (2) trigger pressure during pressure and flow triggering was the only variable that differed among all ventilators; (3) most of the ventilators perform work in the form of low-level pressure support during CPAP; (4) all of the ventilators impose an expiratory work load; and (5) increasing peak inspiratory demand decreased the ability of all ventilators to maintain a constant airway pressure.

Continuous positive airway pressure by definition is the maintenance of airway pressure at a constant level above atmospheric during spontaneous breathing.[30] The application of CPAP has been found useful in many clinical settings: management of cardiogenic pulmonary edema,[31] treatment of atelectasis,[32] maintenance of functional residual capacity during endotracheal intubation,[33] reduction of the inspiratory load of auto positive end-expiratory pressure caused by dynamic airway obstruction,[34] and during weaning of patients from ventilatory support.[14,15] The use of the CPAP mode on the mechanical ventilator during spontaneous breathing trials avoids the set-up of additional equipment and enhances patient safety by monitoring and alarming respiratory rate and tidal volume. However, concern regarding the ability of ventilators to provide CPAP without imposing or performing work on patients has existed since CPAP was introduced as an adjunct to spontaneous breathing.

Although our data indicate that the performance of this newest generation of ventilators during CPAP is better than previous generations,[5,6,8,13] these ventilators continue to impose a minor level of inspiratory effort and an

Table 2. Effect of Peak Lung Model Flow on Inspiratory Variables Evaluated

	BEAR		EVITA	GALILEO		PB740	PB840		S300		T BIRD
	Flow	Pressure	Pressure	Flow	Pressure	Flow	Flow	Pressure	Flow	Pressure	Flow
D_T (s)											
40											
Mean	0.11	0.09	0.09	0.10	0.10	0.07	0.07	0.08	0.06	0.07	0.10
SD	0.01	0.01	0.02	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01
60											
Mean	0.11	0.09	0.11	0.11	0.12	0.07	0.08	0.08	0.10*	0.07	0.09
SD	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00
80											
Mean	0.12	0.10	0.11	0.13	0.13	0.07	0.08	0.08	0.09	0.07	0.08
SD	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.01
P_T (cm H_2O)											
40											
Mean	3.14	4.07	2.95	3.81	3.87	2.95	1.43	2.50	1.63	3.05	2.49
SD	0.09	0.23	0.31	0.27	0.32	0.23	0.09	0.09	0.09	0.15	0.17
60											
Mean	4.95*	5.29	4.27	5.96*	6.16*	4.28	2.19	3.06	2.14	3.36	2.97
SD	0.22	0.15	0.00	0.40	0.09	0.40	0.18	0.27	0.15	0.26	0.09
80											
Mean	5.74*	7.16†	6.19†	7.58*	7.69*	4.43	3.21*	3.66	3.10	3.92	4.03
SD	0.15	0.51	0.30	0.64	0.62	0.15	0.15	0.53	0.09	0.09	0.38
PTP_T (cm H_2O × s)											
40											
Mean	0.210	0.171	0.159	0.225	0.240	0.090	0.047	0.091	0.038	0.094	0.132
SD	0.019	0.017	0.049	0.047	0.037	0.007	0.008	0.004	0.008	0.014	0.022
60											
Mean	0.289	0.231	0.247	0.375	0.401	0.121	0.089	0.168	0.118	0.103	0.121
SD	0.041	0.029	0.015	0.033	0.030	0.009	0.007	0.063	0.008	0.003	0.008
80											
Mean	0.394*	0.361*	0.390*	0.507*	0.495*	0.128	0.132	0.133	0.159	0.112	0.145
SD	0.024	0.099	0.034	0.010	0.007	0.008	0.022	0.032	0.012	0.013	0.014
PTP_I (cm H_2O × s)											
40											
Mean	−0.933	−0.154	−0.399	2.576	2.517	1.948	1.370	1.337	1.538	1.378	0.666
SD	0.067	0.293	0.408	0.039	0.230	0.110	0.016	0.009	0.082	0.066	0.254
60											
Mean	−1.146	−0.255	−0.552	1.645*	1.524*	1.008*	1.094	1.232	0.906	0.807	0.426
SD	0.010	0.203	0.069	0.115	0.125	0.053	0.104	0.105	0.028	0.108	0.142
80											
Mean	−0.966	−0.583	−1.432*	0.935*	0.774*	0.807*	0.729	0.935	0.103*	0.110*	0.038
SD	0.085	0.035	0.337	0.045	0.260	0.295	0.007	0.062	0.025	0.072	0.068
VPF (l/s)											
40											
Mean	0.51	0.57	0.52	0.72	0.72	0.69	0.64	0.66	0.62	0.62	0.59
SD	0.01	0.00	0.02	0.00	0.01	0.03	0.00	0.01	0.00	0.00	0.01
60											
Mean	0.83*	0.87*	0.82*	1.03*	1.02*	1.06*	0.88*	0.91*	0.85*	0.85*	0.88*
SD	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.01
80											
Mean	1.12†	1.19†	1.12†	1.27†	1.27†	1.14†	1.24†	1.26†	1.10†	1.11†	1.15†
SD	0.00	0.02	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01
V_T (ml)											
40											
Mean	286	323	312	455	468	395	382	381	401	396	366
SD	10	10	10	1	2	8	5	4	4	6	8
60											
Mean	542*	576*	568*	699*	687*	811*	613*	617*	616*	616*	601*
SD	9	5	3	2	4	1	3	3	3	2	9
80											
Mean	781†	817†	848†	909†	893†	841*	904†	917†	821†	820†	831†
SD	1	1	15	4	4	8	4	4	4	8	3

* $P < 0.05$ *versus* flow demand at 40 l/min. † $P < 0.05$ *versus* flow demand at 40 and 60 l/min.

expiratory workload. In addition, most of them provide a low level of inspiratory pressure support, performing some inspiratory work. Furthermore, the difference between flow and pressure triggering in this generation is much less than that described in previous generations of mechanical ventilators.[25,26]

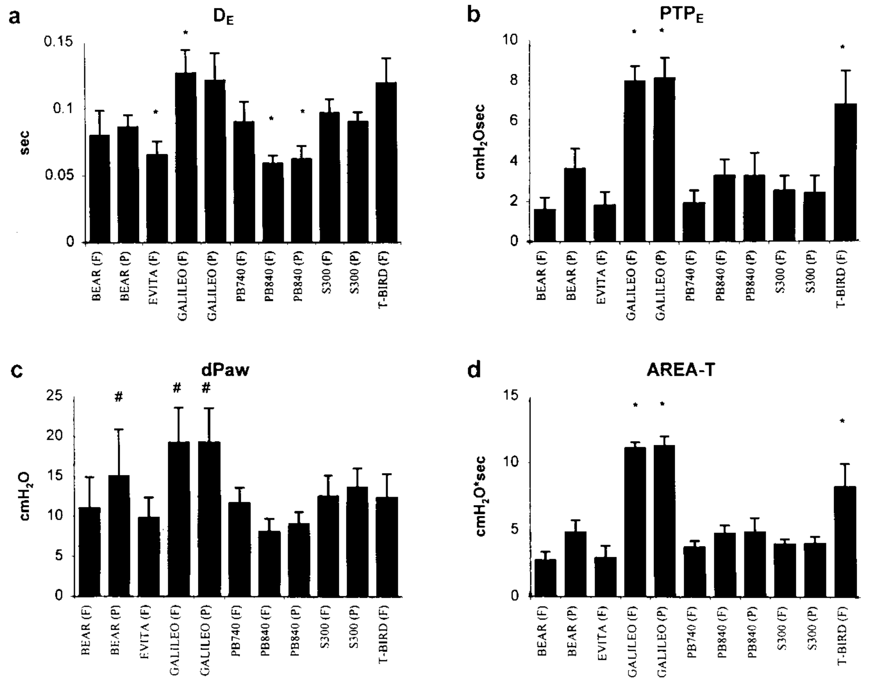

Fig. 5. Expiratory phase variables evaluated: (*A*) expiratory delay time (D_E); (*B*) expiratory pressure time product (PTP_E); (*C*) maximum airway pressure change (dP_{AW}); (*D*) total airway pressure time product (AREA-T). Mean ± SD of all peak flows. *$P < 0.05$ *versus* flow-triggered S300 (*A*, *B*, *D*). #$P < 0.05$ *versus* flow-triggered PB840 (*C*).

Triggering to Inspiration

Triggering of demand flow during CPAP is dependent on the rate at which the ventilator samples airway pressure or flow, the ventilator's mechanical response time, including microprocessor speed, and the type of triggering mechanism used.[11] Based on these factors, it is reasonable to expect flow triggering in CPAP to be more efficient than pressure triggering because by design, on most ventilators, the demand valve must remain open to provide a base flow during flow triggering. An open demand valve should reduce the time for mechanical response of the ventilator in flow triggering. However, we did not observe a trigger time delay or an increase in trigger PTP when flow and pressure triggering were compared in any specific ventilator. We did observe an increase in trigger pressure, although small (3.74 ± 1.89 *vs.* 4.48 ± 1.67 cm H_2O; $P < 0.01$), during pressure triggering in the four ventilators with both pressure and flow triggering. Considering the magnitude of this difference and the fact that no other variables evaluated differed significantly, we question if this difference is clinically relevant. Clearly, the difference we observed is much less than the difference observed by Sassoon and Gruer[11] using a similar lung model with the Nellcor Puritan-Bennett 7200ae (Nellcor Puritan-Bennett Corp.) or differences observed by others in patients.[24,25]

We were surprised at the level of variability among ventilators in those variables that define inspiratory trigger: D_T, P_T, and PTP_T. Ideally, each of these variables should be zero. This is probably unachievable because of mechanical limitations, but the closer to zero the variables are, the more efficient the ventilator is in triggering demand flow. Without proprietary knowledge of the operation of each ventilator, it is impossible to specify why these differences existed among the ventilators. However, our impression is that differences are primarily a result of the mechanical response and the algorithm used to deliver flow during CPAP, since microprocessor time is assumed to be very short.

Target Pressure

An ideal ventilator should deliver CPAP without performing inspiratory work or imposing expiratory resistive work. Only the BEAR and EVITA did not perform inspiratory work, but these two ventilators have a negative inspiratory PTP. In contrast, the GALILEO, PB740, PB840, S300, and T BIRD provided 0.5–2.0 cm H_2O pressure support during CPAP. However, when the integration of total pressure fluctuation from baseline pressure (AREA-T) and the magnitude of the total airway pressure swing (dP_{AW}) are compared (we considered these factors to be an index of the ventilators' ability to maintain the target pressure), the BEAR and EVITA ventilators perform similar to all others except the GALILEO and T BIRD, which demonstrated the large PTP_E.

Ventilators imposing small efforts may be less likely to result in false-positive spontaneous breathing trials, whereas ventilators performing low levels of inspiratory work on patients may be better tolerated for long-term CPAP. However, Esteban *et al.*[35] demonstrated that readiness for ventilator discontinuance could be equally determined with T-piece trials or low-level pressure support spontaneous breathing trials. It is still unclear which of these characteristics is preferable, and additional clinical trials would be needed to provide the answer.

Table 3. Effect of Peak Lung Model Flow on Expiratory Variables Evaluated

	BEAR		EVITA	GALILEO		PB740	PB840		S300		T BIRD
	Flow	Pressure	Pressure	Flow	Pressure	Flow	Flow	Pressure	Flow	Pressure	Flow
D_E (s)											
40											
Mean	0.07	0.09	0.06	0.11	0.11	0.11	0.06	0.07	0.09	0.08	0.13
SD	0.00	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.03
60											
Mean	0.10	0.09	0.07	0.13	0.11	0.08	0.05	0.06	0.10	0.09	0.11
SD	0.01	0.01	0.01	0.01	0.02	0.00	0.01	0.00	0.01	0.01	0.01
80											
Mean	0.07	0.09	0.06	0.14	0.14	0.08	0.06	0.06	0.10	0.09	0.12
SD	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01
P_{Emax} (cm H_2O)											
40											
Mean	2.89	3.68	3.97	10.43	10.38	6.10	4.83	4.73	7.94	7.74	6.57
SD	0.09	0.26	0.40	0.09	0.00	0.16	0.09	0.00	0.15	0.17	0.44
60											
Mean	9.85*	10.83*	5.34*	13.23*	13.08*	8.55*	5.65	6.05*	10.23*	10.28*	9.02*
SD	0.15	0.31	0.16	0.09	0.23	0.15	0.16	0.09	0.16	0.09	0.30
80											
Mean	6.37†	13.97†	6.57*	16.64†	16.49†	8.44†	6.76*	6.92*	12.37†	12.36†	11.80†
SD	0.09	0.51	0.29	0.00	0.27	0.23	0.09	0.09	0.16	0.16	0.29
PTP_E (cm H_2O × s)											
40											
Mean	0.847	2.916	1.219	7.282	7.644	1.627	2.500	2.018	1.710	1.554	5.080
SD	0.104	1.159	0.664	0.105	0.774	0.737	0.101	0.023	0.430	0.394	0.482
60											
Mean	1.912	3.894	1.789	7.696	8.175	1.926	3.074	3.211	2.535	2.179	6.601
SD	0.189	1.077	0.319	0.419	1.155	0.937	0.506	0.434	0.048	0.337	0.863
80											
Mean	2.016	4.101	2.425	8.875	8.490	2.144	4.223	4.561	3.323	3.417	8.652*
SD	0.415	0.453	0.317	0.063	1.242	0.045	0.041	0.340	0.046	0.223	0.543
dP_{AW} (cm H_2O)											
40											
Mean	6.03	7.75	6.92	14.25	14.25	9.06	6.26	7.23	9.57	10.79	9.06
SD	0.15	0.17	0.23	0.23	0.32	0.09	0.15	0.09	0.17	0.09	0.29
60											
Mean	14.80*	16.12*	9.61*	19.19*	19.24*	12.83*	7.83	9.11*	12.37*	13.64*	11.99*
SD	0.34	0.37	0.16	0.35	0.30	0.55	0.09	0.24	0.27	0.23	0.37
80											
Mean	12.11†	21.13†	12.77†	24.22†	24.17†	12.87*	9.97†	10.59*	15.47†	16.28†	15.83†
SD	0.09	0.30	0.08	0.64	0.44	0.09	0.18	0.58	0.24	0.09	0.25
AREA-T (cm H_2O × s)											
40											
Mean	1.903	4.087	2.198	10.985	11.119	3.966	4.039	3.645	3.606	3.545	6.343
SD	0.052	0.751	0.364	0.087	0.667	0.585	0.086	0.031	0.228	0.237	0.466
60											
Mean	3.195	4.930	2.514	10.736	11.320	3.591	4.753	4.905	3.865	3.778	8.073
SD	0.024	1.080	0.253	0.381	0.933	0.649	0.346	0.432	0.067	0.031	0.633
80											
Mean	3.077	5.422	4.036	11.579	11.391	3.567	5.403	5.990	4.380	4.627	10.17*
SD	0.306	0.418	0.231	0.107	0.794	0.051	0.058	0.307	0.040	0.219	0.421

* $P < 0.05$ *versus* flow demand at 40 l/min. † $P < 0.05$ *versus* flow demand at 40 and 60 l/min.

Expiratory Phase

The most unexpected results of this study were the long D_E, the high P_{Emax}, and the impedance to exhalation. These factors produced the high PTP_E and AREA-T observed in some ventilators. It can be argued that our inappropriate setting of sensitivity affected the inspiratory trigger variable. However, these expiratory variables during CPAP were only affected by the operation of the exhalation valve governed by the algorithm set by the manufacturer. The high P_{Emax} observed on many of these ventilators may partially be explained by the lung model square wave flow pattern. As a result, the ventilators end inspiratory flow was high, and a transient high-pressure spike was caused by the recoil of the lung model and the high flow from the ventilator. However, as shown in figure 2 and table 3, P_{Emax} differed greatly among ventilators. PTP_E is primarily a result of the resistance of flow through the exhalation valve. Pressure

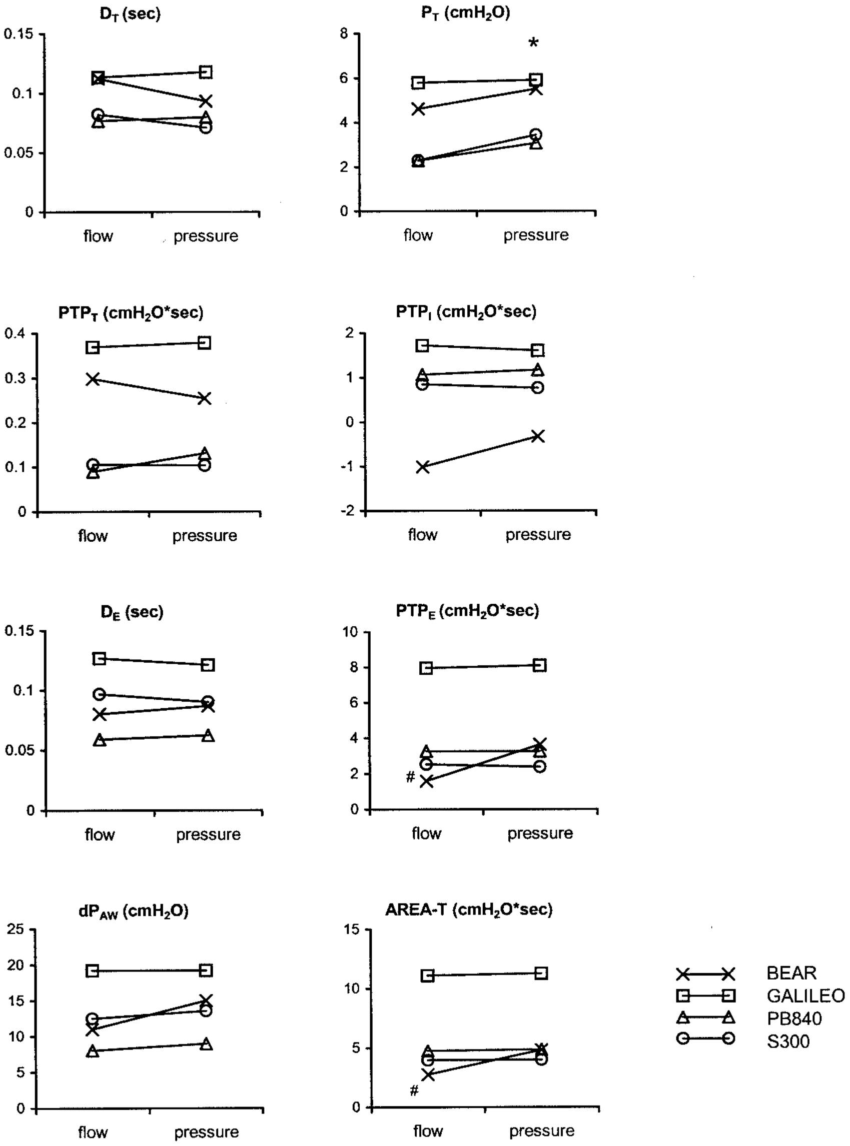

Fig. 6. Effect of triggering method on various parameters. #$P < 0.01$ *versus* flow trigger of same ventilator. *$P < 0.01$ *versus* overall flow triggering. D_T = inspiratory trigger delay time; P_T = inspiratory trigger pressure; PTP_T = triggering pressure time product; PTP_I = inspiratory pressure time product; P_{Emax} = expiratory trigger pressure; D_E = expiratory delay time; dP_{AW} = maximum airway pressure change; PTP_E = expiratory pressure time product; AREA-T = integration of total pressure fluctuation from P_{BL}.

spikes during both triggering and cycling of inspiration may not be observed to the same magnitude in patients because of the location of pressure measurement in many ventilators. Most ventilators measure pressure internally on the inspiratory or expiratory limb. As a result, pressure spikes are dampened. These results raise concerns regarding the expiratory retard and expiratory workload imposed by some of these ventilators, which could be clinically significant in patients with chronic obstructive pulmonary disease.

Effect of Peak Flow

As expected, peak flow rate and tidal volume increased as peak demand flow of the lung model increased. In some ventilators, trigger and inspiratory variables such as P_T, PTP_T, and PTP_I were affected by peak flow rate. Increasing inspiratory peak flow reduced the ability of CPAP to maintain a constant airway pressure. However, peak flow had less of an impact on these ventilators than that observed in previous-generation mechanical ventilators.[32] Interestingly, D_T was not affected in any ventilator. This indicates that once the trigger signal is identified, these ventilators are able to respond in equivalent time regardless of the peak flow. P_{Emax} was affected by the peak flow. This was probably a result of the larger tidal volume with higher peak flow rate. However, on most ventilators, expiratory variables such as D_E and PTP_E were not affected by the demand flow rate.

In some critically ill patients, inspiratory demand may exceed that evaluated in this study. In fact, some critically ill hypoxemic patients may require peak inspiratory flow much greater than 100 l/min. However, we were unable to evaluate the performance of these ventilators at these flows because of the limitations of the lung model. Maximum peak flow generated by the model was 86 l/min. We also attempted to evaluate high inspiratory demand using a Michigan Instrument TLL (Grand Rapids, Michigan) lung model drive by a PB840, but could only generate 88 l/min peak inspiratory demand. As a result we can only rely on the trends observed as flow demand increased from 40 to 80 l/min to speculate on the effects of higher inspiratory demands. Specifically, performance of all ventilators can be expected to decrease at higher peak inspiratory flows. Trigger pressure and PTP_I as well as P_{Emax}, dP_{aw}, and AREA-T can all be expected to be greater at higher peak inspiratory flows.

Clinical Implications

When these ventilators are compared with data on previous-generation intensive care unit ventilators, it is clear that the overall operation during CPAP has dramatically improved.[1,8,9,13] Older-generation ventilators not only impose greater work loads, but also demonstrate marked differences between flow and pressure triggering favoring flow triggering during CPAP. Our data indicate that on most ventilators during CPAP, little difference between flow and pressure triggering exist, but flow triggering appears to perform slightly better.

Although these data were not collected on patients, the low levels of imposed effort favors the use of most of these ventilators for spontaneous breathing trials, but the low level of work performed may still be a concern. However, our data clearly indicate which ventilators impose and perform the most effort–work and provides direction for ventilator selection. Clinical trials are needed before any of these ventilators can be unequivocally recommended for use during spontaneous breathing trials. However, our impression is that the amount of work imposed or performed by these ventilators is clinically insignificant for most patients.

Controversy exists over the benefit of pressure *versus* flow triggering during assisted ventilation.[19–25] Some studies[19,21,22] found no difference between the two, whereas others favored flow triggering.[23–25] Methods used to set triggering and modes evaluated may partially explain these difference.

Our data on the Servo 300 is consistent with data from Aslanian *et al.*[25] and Tütüncü *et al.*[22] During pressure support in 16 adults, Tütüncü *et al.* found no difference between pressure and flow triggering with the pressure trigger set at 1.0 cm H_2O and the flow trigger at 0.7–2.0 l/min. During a lung model evaluation, Aslanian *et al.* also found little difference during pressure support when the flow trigger was set at 1 l/min and pressure trigger at 0.5 cm H_2O, which in our experience are equivalent settings.[21] However, during an evaluation on patients, Aslanian *et al.* set flow triggering at 2 l/min and pressure triggering at 2 cm H_2O. These results favored flow triggering. Ideally, both should be set as we set sensitivity, at the most sensitive setting not causing self triggering. Unfortunately, we did not evaluate assisted ventilation. However, considering the differences between pressure and flow triggering during CPAP on older-generation ventilators and the improvement observed on the newer ventilators, we would expect less response difference during assisted ventilation than that observed in some comparisons.[23–25]

Limitations

The most important limitation of this study is the fact that it was performed on a lung model instead of patients. It is possible that performance on patients may differ greatly from that demonstrated here. Specifically, the “pleural space” of our model is always open to atmosphere, unlike the normal human pleural cavity. However, this model allows the determination of the onset of inspiration by deflection in pleural pressure. Peak inspiratory flows of only 40–80 l/min were evaluated on all ventilators because of the limitations of the lung model. In critically ill hypoxemic patients, peak inspiratory flows may greatly exceed those evaluated. It is thus difficult to predict the performance of these ventilators outside the flow range studied. Water in the ventilator circuit may cause autotriggering. The fact that we did not operate the ventilator humidifier may have affected ventilator response. In addition, only one level of CPAP in a single ventilator of each type was evaluated. Our pilot data indicated that CPAP level did not affect the evaluated variables, but we cannot comment on the variability in ventilators from a single manufacturer. We also did not evaluate the effect of pressure and flow triggering during assisted ventilation or the impact of auto–positive end-expiratory pressure on the response of these ventilators.

In conclusion, this generation of mechanical ventilators demonstrates a large range of variability during CPAP. However, very little difference exists between pressure and flow triggering. Most of the ventilators evaluated provide low levels of inspiratory pressure support, and all ventilators impose an expiratory work load. Increasing inspiratory peak flow does reduce the ability of CPAP to maintain a constant airway pressure.

All ventilators were specifically provided by the manufacturer for evaluation (Bear Medical Systems Inc., Riverside, CA; Drager Inc., Telford, PA; Nelcor Puritan-Bennett Corp., Carlsbad, CA; Bird Products Corp., Palm Springs, CA; Hamilton Medical AG, Rhazuns, Switzerland; Seimens-Elema AB, Solna, Sweden).

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