Effects of Flow Triggering on Breathing Effort During Partial Ventilatory Support

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The effects of flow triggering (FT) as compared with pressure triggering (PT) on breathing effort have been the focus of several studies, and discrepant results have been reported. In the initial part of our study, a lung model was used to quantify triggering effort (airway pressure–time product, PTPaw) for a range of sensitivity settings in nine new-generation ventilators. A ventilator providing both FT and PT was then used to compare these systems during pressure-support (PSV) and volume-targeted assist-control ventilation (ACV) in eight ventilator-dependent patients, using sensitivity settings (2 L/min for FT and -2 cm H_2O for PT) that had proven significantly different in the initial bench study. Indexes of effort included the esophageal and transdiaphragmatic pressure–time products and inspiratory work of breathing per minute (PTPes/min, PTPdi/min, and Wi/min, respectively). The experimental study revealed significant differences between ventilators in PTPaw at commonly used settings. In two of three ventilators featuring both systems, PTPaw was significantly lower with FT than PT ($p < 0.001$). In the clinical study, FT as compared with PT, was associated with reductions in all indexes of breathing effort during PSV: 16 $\pm$ 6% ($p < 0.001$), 13 $\pm$ 10% ($p < 0.01$), and 14 $\pm$ 12% ($p < 0.05$) for PTPdi/min, PTPes/min, and Wi/min, respectively. By contrast, no differences were found when FT was used during ACV. Although FT reduced triggering effort in both modes ($p < 0.001$), the effects observed during the post-trigger phase differed, and explained the discrepant results between the two modes. We conclude that FT more effectively reduces breathing effort when used in conjunction with a pressure-targeted mode than with a volume-targeted mode, especially when flow delivery is close to or below demand. Aslanian P, El Atrous S, Isabey D, Valente E, Corsi D, Harf A, Lemaire F, Brochard L. Effects of flow triggering on breathing effort during partial ventilatory support.

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Over the past 10 to 15 yr, much insight has been gained into the behavior of critically ill patients undergoing mechanical ventilation. One of the main clinical implications derived from relevant studies is that respiratory muscle exertion may be substantial despite application of ventilatory support (1–3). Among the major factors shown to influence inspiratory effort during assisted forms of ventilation is the effort required to trigger the ventilator (3, 4). The widespread introduction of pressure-triggered demand valves on most mechanical ventilators prompted several studies which demonstrated that such systems imposed more work of breathing (WOB) than traditional continuous-flow systems (5–7). More recently, some manufacturers have incorporated flow-triggering (FT) technology into newer-generation microprocessor-based ventilators, and the characteristics of the trigger function have been described in detail for some ventilators (8).

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Most experimental and clinical studies thus far have focused on the use of FT systems with continuous positive airway pressure (CPAP) (9–14). FT has usually been associated with a reduction in breathing effort as compared with pressure triggering (PT), although a significant benefit was not found consistently in all studies (9, 10, 13, 15). Such investigations suggest that the physiologic response to mechanical ventilation may be substantially affected by ventilator design and performance. This claim has also been supported by recent studies comparing pressure support ventilation as delivered by different devices (16, 17). Rigorously obtained, comparative data in this area are, however, relatively scarce. Although the influence of FT systems has also been assessed during synchronized intermittent mandatory ventilation (SIMV) (18, 19), very few data exist regarding their use in patients requiring assisted modes such as pressure support (PSV) or assist-control ventilation (ACV). It can be argued that these represent the more relevant situations in which to assess the effect of such systems.

In view of these observations, we undertook a study aimed at characterizing the performance of the triggering mechanisms of nine commercially available adult intensive care ventilators. In the first part of the study, a lung model was used to compare the triggering effort at several sensitivity settings for

each ventilator. The purpose of the second part of the study was to determine the clinical impact of differences found in the initial bench study. Specifically, the influence of FT on inspiratory effort was assessed in critically ill, ventilator-dependent patients during both PSV and ACV. We selected, for the clinical study, sensitivity settings that produced significant differences in the bench study, to see whether experimental *in vitro* results would predict the *in vivo* results.

METHODS

Experimental-Lung-Model Study

A two-chamber test lung (Michigan Instruments Inc., Grand Rapids, MI) was used to stimulate spontaneous breathing, as shown in Figure 1. One chamber (driving chamber) was connected to and powered by a CPU ventilator (Ohmeda, Maurepas, France), whereas the other (experimental chamber) was connected to the ventilator being tested. The chambers were connected by a small metal lifting bar such that inflation of the driving chamber generated subatmospheric pressure in the experimental chamber, providing the trigger signal for the test ventilator. The compliance of the driving chamber was set at 30 ml/cm H_2O, and that of the experimental chamber at 60 ml/cm H_2O. The CPU ventilator was adjusted to deliver a constant inspiratory flow of 30 L/min with an inspiratory time of 0.6 s at a frequency of 12 cycles/min. These settings provided a simulated effort of moderate intensity, as quantified by the slope of the pressure decrease in the experimental chamber of 4 cm H_2O/100 ms during airway occlusion (i.e., equivalent to an occlusion pressure, or $P_{0.1}$, of 4 cm H_2O). The test ventilator was set in the PSV mode at 15 cm H_2O and at zero positive end-expiratory pressure (PEEP). Because of the compliance of the experimental chamber, these settings ensured that once flow was triggered, the experimental chamber received approximately three times more volume than the driving chamber. Consequently, it was displaced in synchrony with, and independently of, the driving chamber. Each ventilator was connected to its respective chamber with an 8-mm-ID endotracheal tube (ETT) and a standard ventilator circuit, from which the humidifier was omitted.

The nine commercial ventilators evaluated were the Puritan–Bennett 7200ae (Puritan–Bennett Corp., Carlsbad, CA); Siemens Servo 300 (SV 300) and Servo 900C (SV 900C) (Siemens–Elema, Solna, Sweden); Bird 8400ST (Bird Products Corp., Palm Springs, CA); Taema Cesar (Taema, Antony, France); Hamilton Veolar (Hamilton Medical, Rhäzüns, Switzerland); Newport Wave (Newport Medical Instruments, Newport Beach, CA); Dräger Evita 2 (Drägerwerk, Lübeck, Germany), and Engström Erica (Engström Medical, Bromma, Sweden). A range of sensitivity settings was tested for the triggering system(s) of each ventilator (i.e., -0.5 to -2 cm H_2O for PT and 1 to 5 L/min for FT). Before the study, each ventilator was inspected and upgraded as necessary by the manufacturer. This experimental evaluation was conducted as part of a more widespread assessment of mechanical ventilatory equipment undertaken by a specialized working group (Groupe de Travail sur les Respirateurs, Assistance Publique–Hôpitaux de Paris).

Measurements and calculations. A Fleisch No. 2 pneumotachograph (Fleisch, Lausanne, Switzerland) was inserted between the ETT and the circuit Y connector of the tested ventilator. Airway pressure was measured with a differential pressure transducer (MP 45 $\pm$ 100 cm H_2O; Validyne, Northridge, CA) placed at the distal end of the circuit. Signals were recorded at 128 Hz using an analog/numeric data-acquisition system (MP100; Biopac Systems, Goleta, CA) and were stored in a personal computer for subsequent analysis.

At each sensitivity setting tested, triggering performance was assessed according to three criteria: (*1*) the time delay (TD) between onset of the airway pressure (Paw) decay and flow delivery; (*2*) the decrease in Paw (ΔPaw) measured from its baseline value to its nadir; and (*3*) the airway pressure–time product per cycle (PTPaw/cycle) during the trigger phase, defined as the area under the Paw signal during the TD interval.

Statistics. Means and standard deviations for TD, ΔPaw, and PTPaw/cycle were determined from a total of six respiratory cycles. Comparisons of PTPaw/cycle among ventilators were made through one-way analysis of variance (ANOVA) for all ventilators at one particular trigger setting: 1 cm H_2O for PT systems for 2 L/min for FT systems. We present this statistical comparison because it well reflects the differences among ventilators. Other comparisons concerned the effect of changing the sensitivity for a given ventilator, and comparisons between FT and PT systems on the same ventilator. When appropriate (significant F value), Scheffe's F test was used for comparing means. A value of $p < 0.05$ was considered significant. Differences between PT and FT systems of the same ventilator were analyzed with the paired *t* test.

Clinical Study

Eight patients admitted to the medical intensive care unit of our institution and recovering from various conditions were studied. All were orotracheally intubated (7.5 to 8.5-mm-ID ETT) and mechanically ventilated with a Puritan–Bennett 7200ae ventilator (Puritan–Bennett Corp.). This ventilator was chosen for the clinical study because (*1*) it offers the possibility of using both PT and FT with all assisted modes; (*2*) published data exist for this ventilator with regard to other ventila-

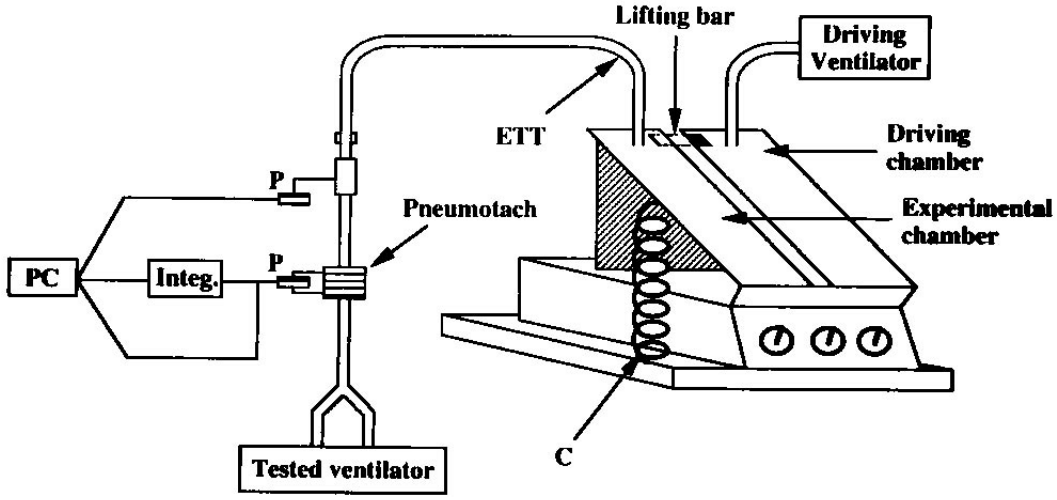

Figure 1. Illustration of lung model and experimental set-up used to simulate spontaneous breathing. C = compliance; ETT = endotracheal tube; Integ. = integrator; P = pressure transducer; PC = personal computer.

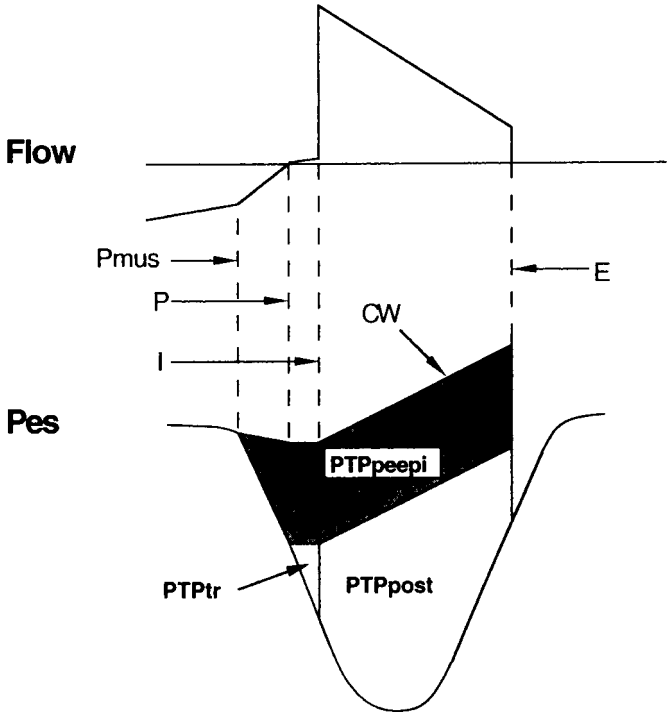

Figure 2. Illustration of method used to partition PTPes into its constituent components: effort required to overcome PEEPi (PTPpeep$_i$), triggering effort (PTPtr), and post-triggering effort (PTPpost). PTPpeep$_i$ constitutes a load imposed during the whole inspiration, whereas the triggering effort represents only a short delay before being transformed into volume. Indeed, PEEPi modifies the starting point of the effort, and the energy dissipated to overcome this inspiratory threshold load is not recovered during the rest of inspiration. The calculation of PTPpeep$_i$ is referenced to the static chest-wall relaxation line. By contrast, once the ventilator is triggered, the effort previously exerted to trigger the ventilator becomes effective for displacing volume; with regard to the efficacy of the inspiratory effort, the trigger system therefore only imposes a delay. Quantitatively, it is only a small part of the total effort. Pes = esophageal pressure; Pmus = onset of inspiratory effort; P = first point of zero flow; I = onset of inspiratory flow; E = onset of expiration; CW = chest wall static recoil pressure vs time relationship.

tory modes; (*3*) the *in vitro* study revealed significant differences between the two triggering systems of this ventilator. Results may therefore be different for other ventilators.

Patients were recruited consecutively when they exhibited spontaneous breathing efforts and were ventilated in the pressure-support mode as prescribed by the attending physician. Patients were excluded only if hemodynamically unstable or if an abnormal respiratory drive was deemed attributable to a diagnosed neurologic condition. At the time of the study, all patients were considered ventilator-dependent, in that reduction of the pressure support level at 10 cm H_2O or below, or a T-piece trial, on the same day or the day before the study began, was associated with signs of respiratory distress. Some patients were receiving low-dose benzodiazepines and/or opioid analgesia, but all were easily aroused and could obey verbal commands. A physician not involved in the study was present to provide for patient care. The investigative protocol was approved by the local ethics committee, and informed consent was obtained from each patient or the patient's family.

Flow was measured with a Fleisch No. 2 pneumotachograph inserted between the Y piece of the ventilator circuit and the ETT, and connected to a differential pressure transducer (Validyne; MP45 ± 2 cm H_2O). V_T was obtained by integration of the flow signal. Airway pressure was measured at the proximal end of the ETT, using a differential pressure transducer (Validyne; MP45 ± 100 cm H_2O). Esophageal (Pes) and gastric (Pga) pressures were measured with a double-lumen catheter (Marquat, Boissy Saint Léger, France) equipped with two thin latex balloons inserted through the patient's nose and advanced until the proximal balloon was in the lower third of the esophagus and the distal balloon in the stomach. Each balloon was filled with 1 ml of air and connected to a differential pressure transducer (Sensym SDX001; ± 70 cm H_2O; Sensym, Plaisir, France). The catheter was inserted a few hours before starting the study. The esophageal balloon was correctly positioned according to a previous description (*20*). Adequate placement of the gastric balloon was ascertained by gentle manual pressure on the patient's abdomen to observe fluctuations in Pga, as well as by asking the patient to swallow and verifying that the sharp increase in Pes caused by esophageal contraction was not observed on the Pga tracing. Transdiaphragmatic pressure (Pdi) was obtained by subtracting the Pes signal from the Pga signal. All signals were recorded at 128 Hz, using an analog/numeric data-acquisition system (MP100; Biopac Systems), and were stored in a personal computer for subsequent analysis.

Study protocol. Patients were studied in the semirecumbent position. According to standard clinical practice in our unit, the pressure support level had previously been titrated by the attending physician to minimize or abolish clinical signs of respiratory distress, such as accessory muscle use, and was used with a respiratory rate ranging between 15 and 30 breaths/min; special care was taken, by examining the flow tracing on the monitor of the ventilator, to minimize the occur-

TABLE 1

MEAN VALUES (± SD) FOR TIME DELAY (ms) AT EACH SENSITIVITY SETTING

	PT Sensitivity (*cm H_2O*)			FT Sensitivity (*L/min*)				
Ventilator	−0.5	−1	−2	1	2	3	4	5
PB 7200ae*	84 ± 4	99 ± 9	113 ± 4	68 ± 4	70 ± 5	73 ± 4	81 ± 4	86 ± 5
SV 300†	59 ± 4	75 ± 4	79 ± 3	47 ± 5	49 ± 4	—	—	—
SV 900C	59 ± 4	66 ± 6	69 ± 3	NA	NA	NA	NA	NA
Bird 8400ST	NA	79 ± 6	118 ± 9	92 ± 6	94 ± 8	110 ± 8	113 ± 4	118 ± 6
Cesar	63 ± 5	75 ± 4	106 ± 4	NA	NA	NA	NA	NA
Veolar	95 ± 3	100 ± 6	131 ± 3	NA	NA	NA	NA	NA
Wave‡	36 ± 4	73 ± 4	200 ± 16	NA	NA	NA	NA	NA
Evita 2	NA	NA	NA	48 ± 3	52 ± 4	51 ± 7	52 ± 7	52 ± 8
Erica†	NA	NA	NA	125 ± 5	200 ± 6	—	—	—

Definition of abbreviations: PT = presure triggering; FT = flow triggering; NA = not available.

* Baseline flow during flow triggering was set at 10 L/min.

† Flow-triggering settings indicated as 1 and 2 L/min for these ventilators are actually maximum and intermediate sensitivities, respectively, adjusted on a nonnumerical dial.

‡ Pressure triggering with this ventilator operates with a baseline flow, which was set at 10 L/min.

TABLE 2

MEAN VALUES (± SD) FOR AIRWAY PRESSURE DROP (cm H_2O) AT EACH SENSITIVITY SETTING

	PT Sensitivity (*cm H_2O*)			FT Sensitivity (*L/min*)				
Ventilator	−0.5	−1	−2	1	2	3	4	5
PB 7200ae*	2.5 ± 0.2	3.1 ± 0.3	3.5 ± 0.2	1.6 ± 0.0	1.6 ± 0.1	1.7 ± 0.1	2.0 ± 0.1	2.1 ± 0.1
SV 300†	1.1 ± 0.1	2.9 ± 0.3	2.9 ± 0.3	1.4 ± 0.1	1.4 ± 0.1	—	—	—
SV 900C	2.6 ± 0.1	2.9 ± 0.2	3.0 ± 0.1	NA	NA	NA	NA	NA
Bird 8400ST	NA	2.8 ± 0.1	3.1 ± 0.1	2.9 ± 0.1	2.9 ± 0.1	3.2 ± 0.4	3.4 ± 0.2	3.3 ± 0.2
Cesar	2.2 ± 0.1	2.7 ± 0.1	3.6 ± 0.1	NA	NA	NA	NA	NA
Veolar	3.5 ± 0.1	3.6 ± 0.1	4.4 ± 0.1	NA	NA	NA	NA	NA
Wave‡	1.1 ± 0.1	1.1 ± 0.0	2.8 ± 0.1	NA	NA	NA	NA	NA
Evita 2	NA	NA	NA	1.6 ± 0.1	1.9 ± 0.2	1.8 ± 0.1	1.8 ± 0.2	1.8 ± 0.1
Erica†	NA	NA	NA	2.0 ± 0.0	2.4 ± 0.0	—	—	—

Definition of abbreviations: PT = presure triggering; FT = flow triggering; NA = not available.

* Baseline flow during flow triggering was set at 10 L/min.

† Flow-triggering settings indicated as 1 and 2 L/min for these ventilators are actually maximum and intermediate sensitivities, respectively, adjusted on a nonnumerical dial.

‡ Pressure triggering with this ventilator operates with a baseline flow, which was set at 10 L/min.

rence of detectable ineffective inspiratory efforts. Four patients were ventilated with a PEEP of 5 cm H_2O to optimize oxygenation or counteract dynamic hyperinflation. The PEEP level and the $F_{I_{O_2}}$ were maintained constant throughout the study.

In the first part of the protocol, two trigger sensitivities were applied in random order during PSV: (*1*) PT at a set sensitivity of −2 cm H_2O; and (*2*) FT at a baseline flow of 10 L/min and a set sensitivity of 2 L/min. We chose these two settings because they are commonly used, and also because they differed significantly in the bench study. In the second part of the protocol, patients were switched to constant-flow ACV with the following settings: a minimum backup frequency such that every breath was patient-initiated; a V_T matched for the mean value obtained during PSV for each patient; and a peak flow rate of 50 L/min. The same two trigger sensitivities were then randomly applied as during PSV.

Data were recorded during a 5-min period after a 15-min period in each experimental condition, once a stable breathing pattern was observed. Endotracheal suctioning was performed before each study period, and a 30-min period was allowed during the transition from PSV to ACV to enable patients to become accustomed to the change in ventilatory mode.

Data analysis. Breathing pattern and minute ventilation ($\dot{V}_E$) were determined from the flow tracing. The pressure–time product per breath for the diaphragm (PTPdi/br) was obtained by measuring the area under the Pdi signal from the onset of its positive deflection to its return to baseline. The esophageal pressure–time product per breath (PTPes/br) was obtained by measuring the area under the Pes signal between the onset of inspiratory effort and the end of inspiration, and was referred to the chest wall (CW) static recoil pressure–time relationship (21). The inspiratory work of breathing per breath (Wi/br) was obtained from a Campbell diagram by computing the area subtended by the inspired volume–Pes curve and the relaxation pressure–volume curve of the CW, taking into account intrinsic PEEP (PEEPi). The CW relaxation curve was plotted for each patient during a brief period of controlled mechanical ventilation applied at the end of the experiment and characterized by respiratory muscle relaxation, as indicated by the lack of visible inspiratory efforts and the absence of negative swings in Pes preceding mechanical inflation. PTPdi per minute (PTPdi/min), PTPes per minute (PTPes/min), and Wi per minute (Wi/min) were calculated as PTPdi/br, PTPes/br, and Wi/br, respectively, multiplied by respiratory rate. As a further step, individual breaths used for data analysis were used to create the average breath for each patient in each of the four study conditions, as previously described (19, 22). Through the use of a methodology adapted from that of Sassoon and colleagues (21), this allowed partitioning of PTPes/br into its different components (Figure 2), consisting of: (*1*) effort required to overcome PEEPi ($PTPpeep_i$); (*2*) effort required to trigger gas flow from the ventilator (PTPtr); and (*3*) effort exerted in the post-trigger phase (PTPpost). Dynamic PEEPi was calculated as the difference in Pes between the onset of its negative deflection and

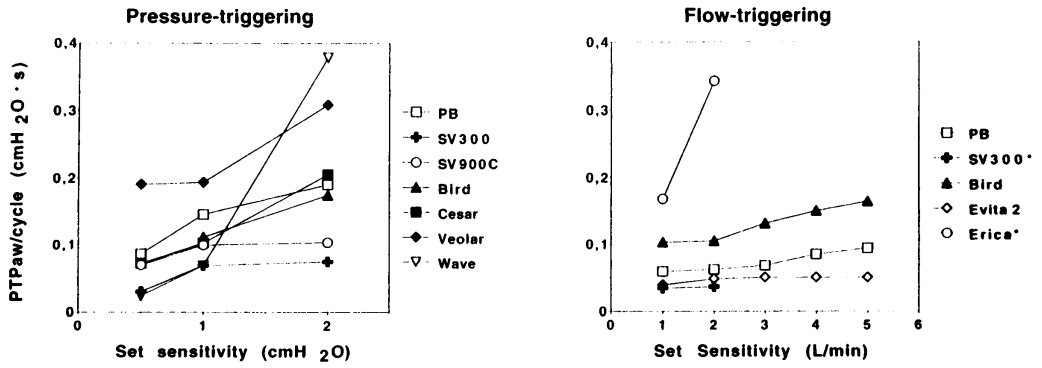

Figure 3. Values for airway pressure–time product per cycle (PTPaw/cycle) obtained at selected sensitivity settings in the nine ventilators tested. Note that three ventilators (PB, SV 300, and Bird) offer both PT and FT options. Error bars are omitted for clarity. *See text* for further details. *Flow-triggering settings indicated as 1 and 2 L/min for these ventilators are actually maximum and intermediate sensitivities, respectively, adjusted on a nonnumerical dial.

TABLE 3

PATIENT CHARACTERISTICS

Patient No.	Sex	Age (*yr*)	Weight (*kg*)	Diagnosis on Admission	Days on MV	PS Level (*cm H_2O*)	$F_{I_{O_2}}$	Pa_{O_2}* (*mm Hg*)	pH*
1	F	74	78	CABG	7	15	0.40	122	7.43
2	F	52	48	Sepsis, COPD	16	15	0.40	75	7.32
3	F	63	86	Septic shock	29	12	0.40	133	7.44
4	F	76	69	COPD exacerbation	15	15	0.30	94	7.35
5	M	78	80	Pneumonia	7	18	0.40	80	7.37
6	F	46	71	Pneumonia	3	22	0.50	73	7.40
7	M	53	56	TEN; aspiration	2	20	0.50	79	7.43
8	M	51	65	OLT; sepsis	12	12	0.35	135	7.34

Definition of abbreviations: MV = mechanical ventilation; PS = pressure support; $F_{I_{O_2}}$ = fractional inspired oxygen concentration; CABG = coronary artery bypass grafting; COPD = chronic obstructive pulmonary disease; TEN = toxic epidermal necrolysis; OLT = orthotopic liver transplantation.

* Data obtained during PS just prior to the study.

the first point of zero flow. This value was corrected for the presence of expiratory muscle activity during expiration as detected on Pga tracings, according to the method of Lessard and associates (23).

After exclusion of cycles plagued by artifact (cough, esophageal spasm), the last 2 min of recorded data (at least 30 breaths) were used for analysis in each condition.

Statistics. Data are given as mean ± SD. Comparisons between PT and FT in each mode were made with the paired *t* test.

RESULTS

Experimental Study

Mean values for TD and ΔPaw in all experimental conditions are shown in Tables 1 and 2, respectively. Results for PTPaw/cycle are illustrated in Figure 3. At a set PT sensitivity of -1 cm H_2O, significant differences ($p < 0.05$) were found between ventilators. The PTPaw/cycle was lowest for the SV 300 and Wave ventilators. The SV 900C, Bird 8400ST, and Cesar ventilators were statistically equivalent, with a PTPaw/cycle significantly lower than that of the PB 7200ae. The poorest performance (highest PTPaw) was obtained with the Veolar ventilator. At a setting of -2 cm H_2O, an increase in PTPaw/cycle was seen for all ventilators, from almost negligible for both the SV 300 and SV 900C ventilators to more than a five-fold increase with the Wave ventilator.

At an FT setting of 2 L/min, the PTPaw/cycle was lowest for the SV 300 and the Evita 2 ventilators. The PTPaw/cycle was slightly but significantly higher for the PB 7200ae and by far highest for the Erica ventilator.

For both the SV 300 and PB 7200ae ventilators, PTPaw/cycle was significantly lower ($p < 0.001$) at the FT sensitivity of 2 L/min than at the PT setting of -1 cm H_2O, whereas no significant difference was found with the Bird 8400ST instrument.

TABLE 4

VENTILATORY PARAMETERS AND INDEXES OF BREATHING EFFORT DURING THE FOUR STUDY CONDITIONS

	PSV		ACV	
	PT	FT	PT	FT
Minute ventilation, L/min	10.0 ± 1.7	10.2 ± 1.3	10.6 ± 2.1	10.4 ± 1.9
Respiratory rate, min^{-1}	21.3 ± 2.7	20.9 ± 3.0	21.5 ± 2.1	21.3 ± 2.6
V_T, L	0.48 ± 0.10	0.50 ± 0.09	0.50 ± 0.13	0.50 ± 0.13
T_I/T_{tot}	0.27 ± 0.07	0.29 ± 0.08	0.28 ± 0.04	0.27 ± 0.05
V_T/T_I, L/s	0.66 ± 0.25	0.64 ± 0.23	0.65 ± 0.11	0.66 ± 0.11
PEEPi, dyn, cm H_2O	2.9 ± 2.1	2.5 ± 1.9*	2.8 ± 2.1	2.5 ± 2.0*
Paw_{insp}, cm H_2O	11.5 ± 3.7	12.5 ± 3.8†	11.3 ± 4.0	12.1 ± 4.9
PTPes, cm $H_2O \cdot$ s/min	193 ± 77	168 ± 67†	176 ± 77	169 ± 87
PTPdi, cm $H_2O \cdot$ s/min	191 ± 80	161 ± 68‡	172 ± 83	168 ± 94
Wi/min, Joules/min	12.2 ± 6.8	10.5 ± 5.9*	11.6 ± 6.8	11.7 ± 7.6
Wi/L, Joules/L	1.16 ± 0.53	1.00 ± 0.49*	1.05 ± 0.48	1.09 ± 0.61

Definition of abbreviations: PSV = pressure support ventilation; ACV = assist-control ventilation; PT = pressure-triggering; FT = flow-triggering; V_T = tidal volume; T_I/T_{tot} = ratio of inspiratory time to total breath duration; V_T/T_I = mean inspiratory flow; PEEPi, dyn = dynamic intrinsic positive end-expiratory pressure; Paw_{insp} = mean inspiratory airway pressure; PTPes = esophageal pressure-time product; PTPdi = transdiaphragmatic pressure-time product; Wi = inspiratory work of breathing.

* $p < 0.05$, paired *t* test versus PT for the same ventilatory mode.

† $p < 0.01$, paired *t* test versus PT for the same ventilatory mode.

‡ $p < 0.001$, paired *t* test versus PT for the same ventilatory mode.

Clinical Study

The salient demographic and clinical features of the eight patients studied are presented in Table 3. Ventilatory parameters and indexes of breathing effort during the four study conditions are indicated in Table 4. Individual values for PTPdi/br in each mode are shown in Figure 4.

No differences in breathing pattern between PT and FT were observed during either PSV or ACV. In the PSV mode, PTPdi/min was lower with FT than with PT by 16% ($p < 0.001$), PTPes/min was lower by 13% ($p < 0.01$), and Wi/min was lower by 14% ($p < 0.05$). By contrast, no significant difference was found in any of these parameters during ACV. In

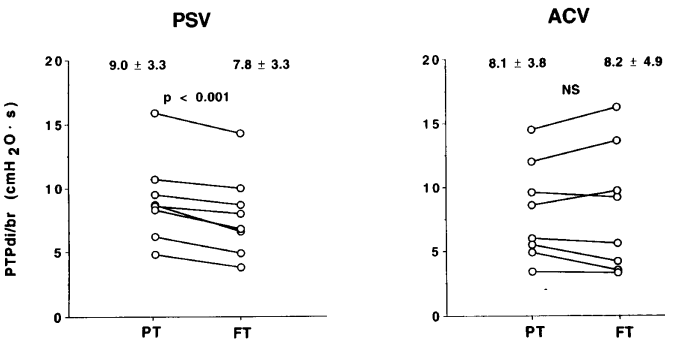

Figure 4. Individual values for transdiaphragmatic pressure–time product per breath (PTPdi/br) in the eight patients enrolled in the study under the four study conditions. A consistent reduction in inspiratory effort was observed with FT in the PSV mode. During ACV, the response to FT was variable, with no significant benefit for the group as a whole.

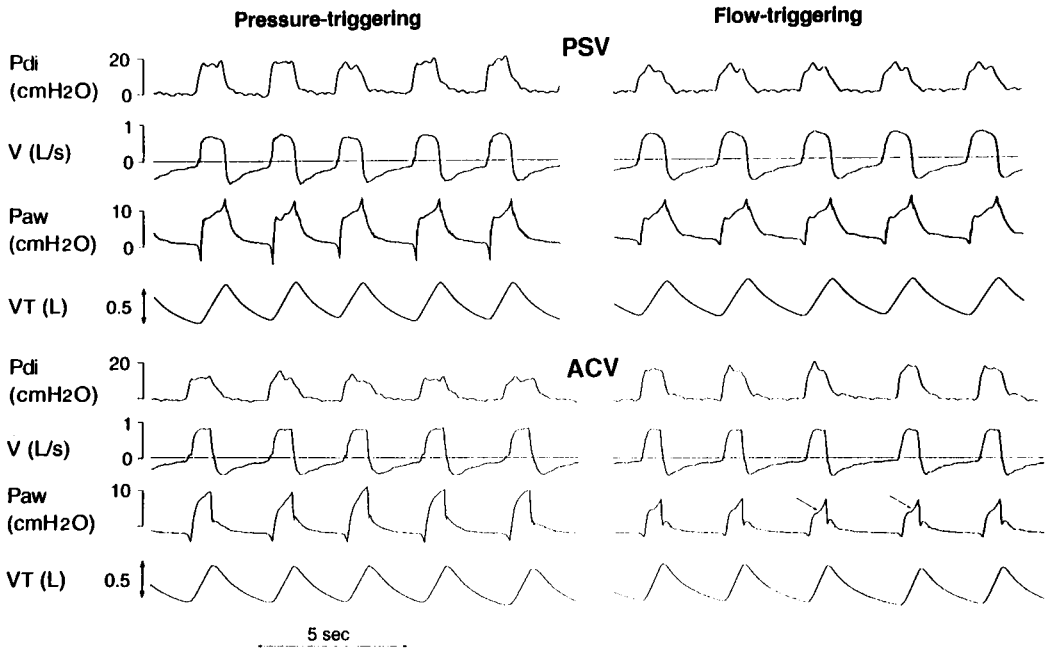

Figure 5. Representative sequence of breaths obtained in Patient 8 during both pressure- and flow-triggered (PSV) (*upper panel*), and pressure- and flow-triggered ACV (*lower panel*). From top to bottom, transdiaphragmatic pressure (Pdi), flow (V), airway pressure (Paw), and tidal volume (V_T). As expected, the decrease in Paw during the trigger phase is smaller with FT in both modes. During PSV, there is decreased muscle effort with FT, with no change in the Paw contour. During ACV, a characteristic scalloping of the Paw contour (*arrows*) occurs during FT, indicating that flow delivery is below patient demand. This is associated with increased effort as compared with pressure-triggered ACV. *See text* for further details.

this mode, FT was actually associated with increased inspiratory muscle effort in three of eight patients (Figure 4). An experimental record from one of these patients (Figure 5) illustrates that swings in Pdi were smaller with FT during PSV, whereas the contrary was observed during ACV, in which flow delivery was probably close to or below demand. Tracings from another patient during ACV (Figure 6) show a different response, with a beneficial impact of FT in this case.

Table 5 depicts how muscle effort was partitioned under the four study conditions. During both PSV and ACV, there was a decrease in PTPtr and FT ($p < 0.001$), as well as in $PTPpeep_i$ for PSV ($p < 0.05$), but which was not significant for ACV ($p = 0.09$). No significant change was found in PTPpost during FT as compared with PT in the various modes.

During PSV, mean inspiratory airway pressure (a measure of the inspiratory assist provided by the ventilator) was significantly higher with FT than with PT ($p < 0.01$), whereas no significant difference was found during ACV (Table 4). The use of FT was associated with a slight but significant reduction in dynamic PEEPi during both PSV and ACV ($p < 0.05$). After close inspection of all tracings, ineffective inspiratory efforts were found to be rare (no more than 2/min in any patient), and no episodes of ventilator autocycling were detected with either PT or FT.

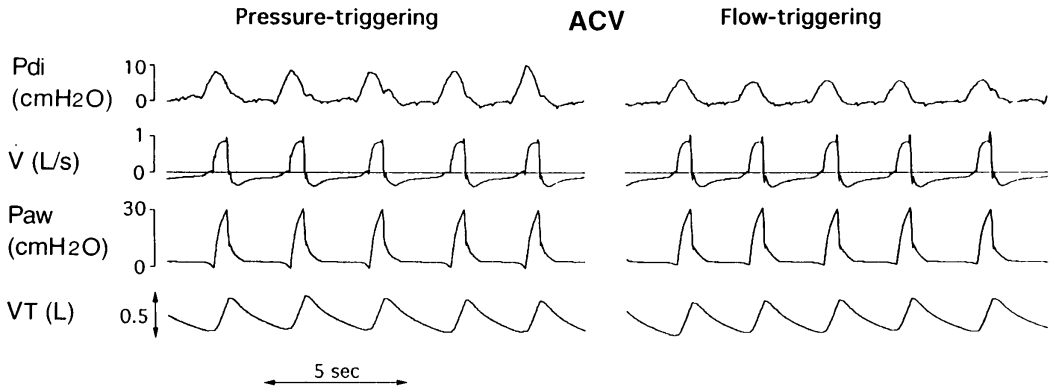

Figure 6. Experimental record during ACV from Patient 4. Note the smooth increase in the Paw contour during both pressure-triggered and flow-triggered ACV. Swings in Pdi are smaller during application of FT. *See text* for further details.

TABLE 5

PARTITIONING OF INSPIRATORY MUSCLE EFFORT IN EACH OF THE FOUR STUDY CONDITIONS

	PSV		ACV	
	PT	FT	PT	FT
Time delay, ms	155 ± 56	89 ± 23*	141 ± 62	93 ± 47†
Airway pressure drop, cm H_2O	3.8 ± 1.6	2.5 ± 1.4†	3.9 ± 2.1	2.5 ± 1.5†
PTPes, cm $H_2O \cdot$ s/br	9.0 ± 3.3	8.1 ± 3.2*	8.1 ± 3.5	8.0 ± 4.5
$PTPpeep_i$, cm $H_2O \cdot$ s/br	2.8 ± 2.1	2.4 ± 1.9*	2.3 ± 1.9	2.0 ± 1.7
PTPtr, cm $H_2O \cdot$ s/br	0.26 ± 0.06	0.10 ± 0.04†	0.24 ± 0.08	0.10 ± 0.04†
PTPpost, cm $H_2O \cdot$ s/br	5.9 ± 2.9	5.6 ± 2.8	5.6 ± 3.3	5.9 ± 3.9

Definition of abbreviations: tr = trigger phase; post = post-trigger phase. Other abbreviations as in Table 4.

* $p < 0.05$, paired *t* test versus PT for the same ventilatory mode.

† $p < 0.001$, paired *t* test versus PT for the same ventilatory mode.

DISCUSSION

The purpose of the present study was to characterize the performance of the triggering systems incorporated in an array of modern ventilators, and to determine the extent to which differences observed *in vitro* could be extrapolated to the clinical setting.

The results of the experimental part of the study indicate that in general, manufacturers have brought major improvements to the triggering systems of newer-generation ventilators. Lung model studies of older-generation demand-valve systems often reported values for TD and ΔPaw in excess of 400 ms and 6 cm H_2O, respectively, even at maximal sensitivity settings (24–26). Although the results of such experiments depend on the precise settings used, and especially on the intensity of the simulated effort, this suggests that a major improvement exists with modern ventilators. Poor ventilator responsiveness can cause breathing discomfort (27), and may contribute to imposed ventilatory workloads that may hinder the weaning process (28).

Using a methodology similar to that described by Lofaso and associates (17), we estimated triggering effort from the PTPaw/cycle, which integrates both the TD and ΔPaw components of the trigger phase. We found significant differences between ventilators when comparing PTPaw/cycle at identical sensitivity settings. Statistical significance in this context, however, does not necessarily imply relevant differences in the clinical setting. For instance, our experimental data for the SV 300 ventilator showed only a slight, albeit significant, reduction in PTPaw/cycle with FT as compared with PT at −1 and −2 cm H_2O, but two recent studies (29, 30) found no significant differences in superimposed work of breathing when these three sensitivities were applied to patients.

In the clinical part of our study, we compared FT with PT for the PB 7200ae ventilator in eight ventilator-dependent patients during PSV and ACV. We choose settings of 2 cm H_2O for PT and 2 L/min for FT because they are routinely used, and also because they resulted in significant differences in the bench study. Using more sensitive settings for PT might minimize the differences found *in vivo*. However, it might also have involved a higher risk of self triggering. Two recent studies did not find any difference between FT and PT with sensitivity settings of −0.5 or −1 cm H_2O (30, 31). However, one of these studies used the Servo 300 ventilator (30), which, as previously mentioned, may give different results, and the other did not directly measure Pes (31). The triggering system of the PB 7200ae ventilator has been previously extensively studied, but the use of FT in conjunction with these modes had not been systematically studied. The results, however, were unexpected, in that FT was associated with a small but consistent reduction in breathing effort during PSV but not during ACV. In order to determine the pathophysiologic basis for this discrepancy, inspiratory muscle effort was partitioned as shown in Figure 2, and the effects of FT on each component will be discussed separately.

First, there was a reduction in $PTPpeep_i$ with FT during PSV ($p < 0.05$), but which did not reach significance ($p = 0.09$) with ACV. This is consistent with the lower levels of dynamic PEEPi observed during FT in both modes. A decrease in PEEPi with FT has been reported by other investigators, and has been attributed to different mechanisms (14, 19, 32). We observed no differences in breathing pattern that could account for this finding. In two of our patients with a history of severe chronic obstructive pulmonary disease (COPD), the slight additional PEEP induced by the baseline flow during FT may have further reduced the end-expiratory gradient of alveolar-to-airway opening pressure (31). In only one patient was PEEPi partly due to expiratory muscle recruitment as detected on Pga tracings. When corrected for expiratory muscle activity (23), the lower levels of PEEPi found during FT persisted. In the remaining patients, low to moderate levels of PEEPi were caused by dynamic hyperinflation related to high minute ventilation in the setting of increased expiratory resistance (including the ETT, ventilator circuit, and exhalation valve). In normal subjects, FT of the PB 7200ae has been shown to decrease the resistance of both the inhalation and exhalation circuits as compared with PT (9). It must thus be concluded that FT reduced PEEPi mainly through a decrease in expiratory resistance. The reduction in PEEPi contributed to the overall benefit obtained with FT.

Second, FT significantly reduced PTPtr to a similar extent during PSV and ACV. This was fully expected on the basis of the bench study, in which triggering effort was roughly threefold higher at a set sensitivity of −2 cm H_2O than at 2 L/min (0.19 ± 0.02 versus 0.06 ± 0.01 cm $H_2O \cdot$ s/br, $p < 0.001$). This difference is inherent to the trigger mechanism and naturally independent of the ventilatory mode.

Events during the post-trigger phase explain most of the discrepant effects of FT on overall patient effort during PSV and ACV. We found that PTPpost tended to be lower during FT in PSV. This is consistent with results reported by Giuliani and colleagues during SIMV, suggesting that post-triggering effort may depend on the load perceived during the trigger phase (19). On the other hand, the overall response of our patients was quite the opposite during ACV, with a slight (but not significant) increase in PTPpost during FT. The patient–ventilator interaction during ACV is quite different from that in PSV, however, and is most easily analyzed with the equation

of motion. During partial ventilatory support, the total pressure required to inflate the respiratory system is provided in part by patient muscle effort (Pmus) and in part by the ventilator (Paw), such that:

$$Pmus + Paw = (Rrs \cdot \dot{V}) + (Ers \cdot V) \quad (1)$$

where Rrs and Ers are respiratory system resistance and elastance, respectively; $\dot{V}$ is flow rate; and V is volume. During constant-flow ACV, both flow and volume are fixed. As a result, Pmus and Paw are inversely related, and, when the patient's demand for flow exceeds the peak flow setting, an increase in Pmus will be accompanied by a decrease in Paw. This behavior was observed in some of our patients during ACV. Tracings from one such patient (Figure 5) illustrate that during flow-triggered ACV, there was a characteristic scalloping of the Paw contour reflecting insufficient flow delivery from the ventilator. This phenomenon was less pronounced during PT, despite an identical peak flow setting of 50 L/min. One can interpret this as indicating that although the flow setting was adequate during PT, it more frequently fell below the patient's flow demand during flow-triggered breaths. This can be related to random fluctuations in inspiratory flow demand (33), although a possible influence of the triggering system on patient drive cannot be excluded. In this patient (Figure 5), although $PTPpeep_i$ and PTPtr were effectively reduced with FT, the additional "wasted effort" during the post-trigger phase (i.e., the amount of additional effort without additional delivered flow) was large enough to offset this benefit, and even resulted in a higher total effort per breath.

It is reasonable to assume that similar breath-by-breath variations in flow demand occurred during PSV, yet FT had a favorable impact on effort in all patients. During PSV, Paw is the fixed (or targeted) variable in the equation of motion. Assuming that the flow-generating capacity of the ventilator is not exceeded, breath-by-breath changes in Pmus can effect similar changes in flow and volume, at least to a certain extent. This would tend to satisfy an increased flow demand and minimize the amount of "wasted effort" in attempting to increase flow. Indeed, although mean V_T in our patients was well matched in both modes, the breath-by-breath variability in volume and flow seen during PSV was, by definition, nonexistent during ACV.

That these differences in patient–ventilator interaction between the two modes explain our findings is further supported by analysis of the pressure generated by the ventilator. In this regard, mean inspiratory airway pressure (Paw_{insp}) is a good index of the ventilator's contribution to the total inflation pressure. During PSV, Paw_{insp} was significantly higher during FT than during PT (Table 4). This was mostly due to an earlier airway pressurization, but also to a smaller decrease in Paw during the trigger phase. By contrast, no significant difference in Paw_{insp} was observed during ACV. Indeed, the greater effort during FT in three patients was associated with a lower Paw_{insp} than during PT, as dictated by the inverse relationship between Pmus and Paw in this mode (Figure 5). This is indicative of the overriding importance of the peak-flow setting in optimizing respiratory muscle relaxation during constant-flow ACV, as previously demonstrated (4, 34, 35).

Our results do not imply that FT cannot reduce breathing effort during ACV. They do, however, suggest, that when the flow setting is in close proximity or inferior to spontaneous flow demand, the effects of random fluctuations in this demand may overshadow the otherwise minor gains related to improved trigger sensitivity. In case of sufficient peak flow, tailored to each patient's needs, FT may have produced a significant benefit. This was in fact the case for three patients in whom FT was as effective during ACV as it was during PSV, and a common feature in these patients was the absence of scalloping of the Paw contour (Figure 6).

In stable COPD patients during the weaning phase, Sassoon and coworkers found that inspiratory work of breathing (Wi) was significantly less during FT than during PT at a CPAP of 0 cm H_2O, but that the difference was not significant at a CPAP of 8 cm H_2O (10). In a later study focusing on SIMV, the same investigators concluded that FT reduced breathing effort (both Wi and PTPes) for spontaneous breaths but not for mandatory breaths (18), a finding similar to ours with regard to volume-targeted breaths. In contrast, Giuliani and coworkers reported reductions in PTPes for both spontaneous and mandatory breaths, during both constant-flow and constant-pressure SIMV (19). In a subsequent study involving a group of patients with COPD and another without evidence of lung disease, Sydow and colleagues found a beneficial effect of FT on Wi in the former but not in the latter group (13). Additionally, in a preliminary communication, Mancebo and associates reported observing a significant decrease in Wi with FT in patients recovering from acute respiratory failure, but no difference in intubated patients suffering from neurologic disorders (11). Although the PT sensitivity in the aforementioned studies was set at $\leq$ 1 cm H_2O, Polese and colleagues recently compared FT with PT at -2 cm H_2O in a mixed group of patients without COPD (12). Indexes of breathing effort decreased by roughly 15% with FT during CPAP, which is in line with the magnitude of reduction observed in our patients during PSV. The cumulative clinical data thus seem to suggest that small but favorable effects of FT on inspiratory effort may be contingent upon factors as diverse as patient drive, ventilator mode and/or settings, and the presence of underlying lung disease.

In conclusion, our results suggest that FT more consistently reduces breathing effort when used in conjunction with a pressure-targeted mode of ventilation such as PSV than during constant-flow ACV. Moreover, the relatively modest benefit observed indicates that the pressure-sensing devices incorporated in most current-generation ventilators are much improved over older ones. It must be stressed, in addition, that a PT sensitivity of -0.5 or -1 cm H_2O, may have even minimized the differences observed in the patients in our study. Also, differences in physiologic parameters do not necessarily imply that these effects will have a significant impact on patients' outcomes. Similar comparisons between the FT and PT systems of other ventilators are lacking. Based on our experimental results with the SV 300 and Bird 8400ST ventilators, the presence of clinically relevant differences with these machines appears unlikely. Significant advances in this area may have to await the development of technology that enables ventilator triggering from signals originating closer to patient effort, such as Pes.

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