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REVIEW ARTICLE

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Characteristics of the ventilator pressure- and flow-trigger variables

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Abstract Pressure- and flow-triggering are available in the Puritan Bennett 7200ae and Siemens SV300. Using a mechanical lung model, we described the characteristics of the pressure- and flow-triggered continuous positive airway pressure (CPAP) of both ventilators. In the Puritan Bennett 7200ae, the pressure-triggered CPAP is characterized by the relatively insufficient flow delivery after the triggering, resulting in a greater lung pressure-time product (total PTP) than the flow-triggered CPAP. Pressure support of 5 cmH_2O results in total PTP less than that with flow-triggered CPAP. In the Siemens SV300, total PTP with pressure- or flow-triggered CPAP is comparable. Total PTP is less with pressure- or flow-triggered CPAP of the Siemens SV300 than that of the Puritan Bennett 7200ae, respectively. The application of small pressure- or flow-triggered pressure support in the Puritan Bennett 7200ae eliminates the difference. The impact of these differences on patient inspiratory muscle work remains to be determined.

Key words Mechanical ventilation · Continuous positive airway pressure · Work of breathing · Pressure-time product · Synchronous intermittent mandatory ventilation

Introduction

With most commonly employed modes of mechanical ventilation, i.e. assist control (AC), synchronous intermittent mandatory ventilation (SIMV), pressure support ventilation (PSV), or during spontaneous breathing with continuous positive airway pressure (CPAP), a set trigger sensitivity has to be reached before the ventilator delivers flow. This set trigger sensitivity, also called the trigger variable, is defined as the variable that is manipulated to deliver flow [1]. The trigger variable may be in the form of a set time, pressure, volume or flow. Time-triggering operates according to a set frequency independent of the patient's spontaneous effort [1]. With pressure-, volume- and flow-triggering, the patient initiates a breath and the ventilator delivers gas flow once the set pressure, volume, or flow is attained. Since volume-triggering is not commonly used [1] we will focus our discussion, in this review article, on pressure- and flow-triggering.

At the time of writing, two microprocessor-based ventilators incorporate both pressure- and flow-triggering for all modes of ventilation: the Puritan Bennett 7200ae (PB 7200ae; Puritan Bennett Corp., Carlsbad, CA) and Siemens Servo 300 (SV300; Siemens-Elema, Solna, Sweden). We will examine the basic characteristics of pressure- and flow-triggered CPAP and where data are available, their impact on inspiratory muscle work [2]. The effect of pressure- and flow-triggered mandatory breaths (i.e. SIMV) on inspiratory muscle work [3] will be discussed only briefly.

Pressure- and flow-triggered CPAP systems are commonly called "demand flow" and "flow by", respectively. In either system, the ventilator delivers fresh gas on demand, i.e. the subject has to initiate a breath for gas delivery. The term "flow by" simply means "continuous base flow" and does not precisely refer to flow triggering. Therefore, to reflect the distinct characteristics of the pressure and flow trigger variables, we will use the following terms – pressure-triggering and flow-triggering – to denote demand flow and flow by systems, respectively.

We examined the characteristics of pressure- and flow-triggered CPAP for both the PB 7200ae and SV300, using a single compartment lung model (TTL model 2600i, Michigan Instruments, Inc., Grand Rapids, MI) as described by Katz et al. [4]. Figure 1 shows the schematic diagram of the lung model and the experimental set up. The lung model consists of two compartments connected with a lifting bar. When one compartment, the simulated "respiratory muscles", is inflated with a ventilator (Puritan Bennett 7200a), the other compartment, the simulated "lung", is passively displaced. The tidal volume of the simulated "lung" was set at 500 ml with a rapid ascending and gradual descending ramp flow waveform with a peak flow rate of $45\,l\cdot min^{-1}$, compliance of $0.020\,l\cdot cmH_2O^{-1}$, and rate of $12\,b\cdot min^{-1}$. A 7.5 mm ID endotracheal (ET) tube was used to connect the simulated "lung" to the test ventilator. The above settings were selected to mimic a respiratory system with a relatively low compliance, high resistance and high ventilatory drive. Because it took different time for the two compartments to empty (due to differences in time constant), it is necessary to apply a positive end-expiratory pressure of 6.0 cmH_2O to the "respiratory muscles" compartment to avoid intercompartments separation at end-expiration. Pressure- and flow-triggered CPAP of 0 cmH_2O were applied to the simulated "lung" with and without a humidifier (Travenol HLC37^{TM}S, Baxter Healthcare Corp., Valencia, CA). The addition of a humidifier was studied in the PB 7200ae only. The application of 5 cmH_2O pressure- and flow-triggered PSV was also evaluated in the PB 7200ae. With pressure-triggered CPAP on both ventilators, the sensitivity was set between 0.5 and 5 cmH_2O. With flow-triggered CPAP of the PB 7200ae, the base flow was set at $10\,l\cdot min^{-1}$ and the flow sensitivity between 1 and $5\,l\cdot min^{-1}$. We selected one base flow value since our previous study in healthy subjects demonstrated that varying the base flow had no significant effect on the inspiratory work of breathing [5]. With flow-triggered CPAP of the SV300, the ventilator automatically provides a base flow of $2\,l\cdot min^{-1}$ and the flow sensitivity was set at $2\,l\cdot min^{-1}$. For the adult setting, flow sensitivity below $2\,l\cdot min^{-1}$ cannot be set precisely.

Pressures at the proximal (P_{AWP}) and the distal (P_{AWD}) end of the ET tube, and within the "lung" (P_{LUNG}) were measured with pressure transducers (MP45 ± 50 cmH_2O, Validyne Corp., Northridge, CA). Flow was measured with a pneumotachograph (No. 2, Fleisch, Lausanne, Switzerland). We defined the interval from onset of inspiratory effort (indicated by the negative

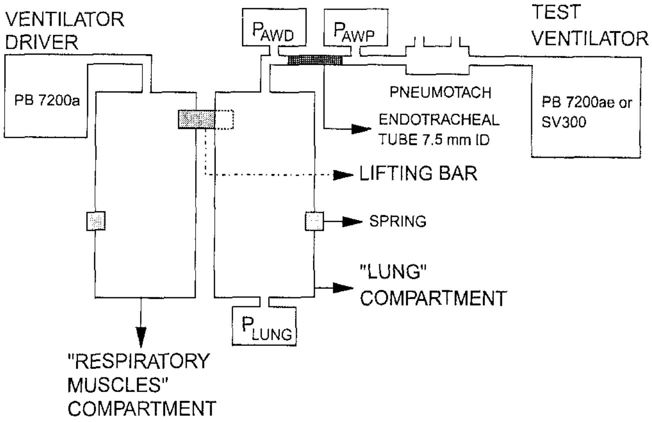

Fig. 1 Schematic illustration of the mechanical lung model and experimental set up. The lifting bar connects the "respiratory muscles" to the "lung" compartment. The spring allows one to set the compliance of the simulated "lung". The compliance of both the simulated "respiratory muscles" and "lung" was set a $0.02\,l\cdot cmH_2O^{-1}$. P_{LUNG} is the pressure within the simulated "lung" measured with a pressure transducer. P_{AWD} and P_{AWP} are the pressures at the distal and proximal end of the endotracheal tube, respectively. PB, Puritan Bennett; SV300, Siemens Servo 300

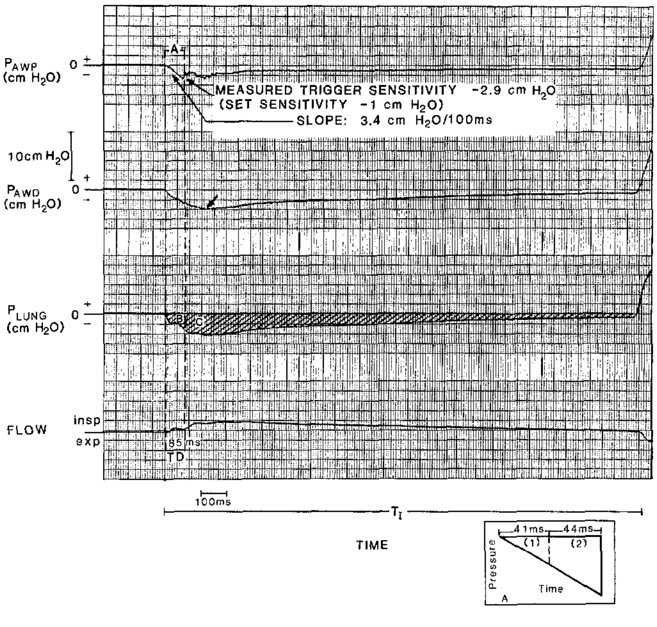

Fig. 2 Pressure-triggered continuous positive airway pressure (0 cmH_2O) of the Puritan Bennett 7200ae applied to a mechanical lung model. P_{AWP}, P_{AWD}, P_{LUNG} are the pressures as indicated in Fig. 1. *Arrow* on P_{AWD} indicates maximum deflection. Note that P_{AWD} remains below atmospheric pressure throughout inspiration. *Part A*, trigger phase: from onset of inspiratory effort (negative deflection of P_{LUNG}) to onset of flow delivery, flow is slightly detectable due to circuit length and compliance; Area B: trigger pressure-time product; *Areas B and C*: total pressure-time product. *TD*, time delay from onset of inspiratory effort to onset of flow. T_I, inspiratory time. *Inset*: A-1 is from onset of inspiratory effort to set pressure sensitivity or trigger threshold: A-2 is from trigger threshold to onset of flow. See text for further explanation

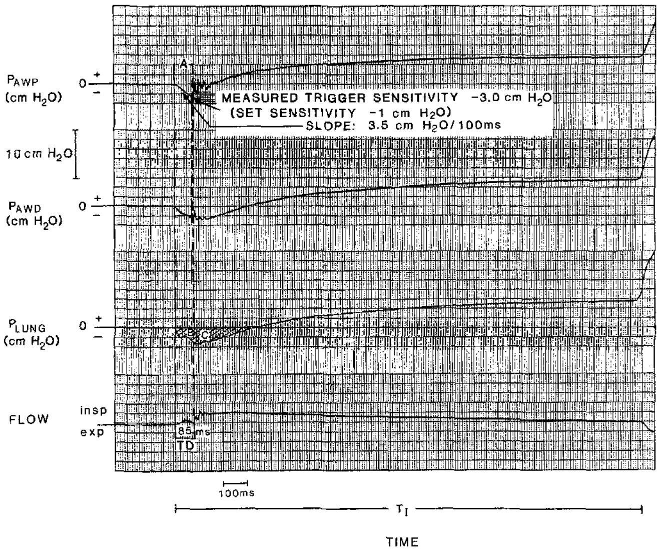

Fig. 3 Pressure-triggered pressure support ventilation (5 cmH_2O) of the Puritan Bennett 7200ae applied to a mechanical lung model. See Fig. 2 for explanation of *part A, areas B and C*, and definition of abbreviations. *Area C* is markedly reduced compared with that of pressure-triggered CPAP (see Fig. 2)

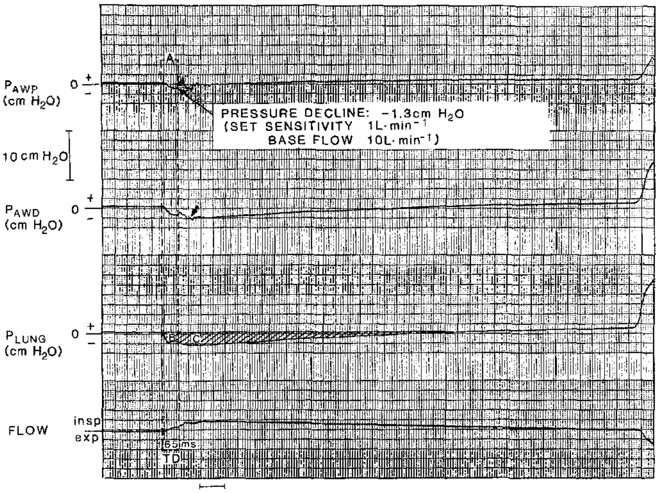

Fig. 4 Flow-triggered continuous positive airway pressure (0 cmH_2O) of the Puritan Bennett 7200ae applied to a mechanical lung model. See Fig. 2 for explanation of *part A, areas B and C*, and definition of abbreviations. The base flow induces a slight positive end-expiratory airway pressure as shown on P_{AWP} tracing. Flow during part A is provided by the base flow. After the trigger phase, P_{AWD} decreases further to a maximum deflection (*short arrow*), then increases gradually to above atmospheric pressure by mid-inspiratory time, suggesting a better flow delivery than with the pressure-triggered CPAP (see Fig. 2)

deflection of P_{LUNG}) to onset of flow delivery as the trigger phase (part A, Figs. 2–5). The time delay from onset of inspiratory effort to onset of fresh gas delivery, and the pressure-time product (PTP) were calculated. The PTP, an estimate of inspiratory effort, was calculated as the area subtended by P_{LUNG} and its baseline over the trigger phase (area B or trigger PTP, Figs. 2–5) and inspiratory time (the sum of area B and C or total PTP, Figs. 2–5). We chose to calculate the PTP instead of the work of breathing since measurement of PTP allows us to estimate inspiratory effort during the trigger phase in which only minimal volume displacement occurs. Our measurements were obtained from one tracing since identical tracings were produced with each of the simulated "lung" breaths.

Pressure-triggered spontaneous breath (CPAP)

With a pressure-triggered CPAP, a set pressure sensitivity must be attained for the ventilator to deliver fresh gas into the inspiratory circuit. Pressure sensitivity is commonly expressed with a negative sign but, for simplicity, we will use the *absolute* term. Hence, an increase or decrease in sensitivity refers to an increase or decrease in the *absolute* value.

A trigger phase during breathing with a pressure-triggered CPAP (PB 7200ae) can be identified by examining the P_{AWP} and P_{AWD} waveforms (part A, Fig. 2). During part A, the subject generates an effort while the proportional solenoid (psol) valve on the inhalation side and the exhalation valve remain closed. We have previously described part A in detail [6]. The slope of part A is determined by the subject's inspiratory drive and muscle strength. Increased inspiratory drive or inspiratory muscle strength shortens the part A interval, and a depressed drive or inspiratory muscle weakness extends it. Part A actually consists of two intervals: i) the time for pressure within the inspiratory circuit to decline to the set sensitivity or true trigger threshold (in this example, 1 cmH_2O) and ii) the response time of the psol valve once the trigger threshold is reached (approximately 6 ms), including the time due to other factors that may affect the duration of part A. These factors include 1) errors due to the speed of the pressure signal, 2) errors due to digital polling of the pressure transducer, 3) errors in the pressure-transducing circuit, 4) discrepancy between the set and actual positive end-expiratory pressure (PEEP), and 5) circuit noise, or any other correction effort to compensate for circuit leaks.

Errors due to the speed of the pressure signal

The speed of the pressure signal approximates the speed of sound, about 0.3 $m \cdot ms^{-1}$ at sea level. This speed of pressure signal is essentially the same within either a rigid or corrugated ventilator tubings (unpublished observation). The pressure transducer that senses the change in pressure within the circuit Y at the onset of inspiratory effort is located within the ventilator and in this study, is separated by a 1.8 m length of tubing. There is an additional 1.8 m of tubing between the circuit Y and the psol valve. Thus, the transit time for a trigger signal generated at the circuit Y to complete the loop from that site to the pressure transducer, psol valve, and back to the circuit Y when onset of flow delivery occurs, measures approximately 12 ms.

Errors due to digital polling of the pressure transducer

In a microprocessor-based ventilator, changes in circuit pressure are polled every X ms. The average increase in part A due this polling time is X/2 ms. For example, the 20 ms polling time in the PB 7200ae increases the duration of part A an average of 10 ms. The SV300 has a very short polling time of 2 ms, this increases part A interval an average of 1 ms.

Errors in the pressure transducing circuit

Errors of pressure transducers can be described by the term $\pm(0.1+3.0\%$ of reading in $cmH_2O)$ [Sanborn, personal communication]. For example, when PEEP/CPAP is zero, the pressure-sensing transducer exhibits an error of $\pm(0.1+0.03\cdot 0)$ or 0.1 cmH_2O (a minus sign shortens and a plus sign lengthens part A).

Errors due to discrepancies between set and actual PEEP

The presence of intrinsic PEEP (PEEPI) increases (in absolute term) the sensitivity relative to the set sensitivity, causing part A to lengthen. On the other hand, with a set PEEP value, leaks in the circuit decrease the actual sensitivity relative to the set sensitivity and shorten part A.

Errors due to noise in the circuit

Such noise includes PEEP-loss compensatory flow, other ventilator correction-based routines aimed at enhancing transducer sensitivity or accuracy. Efforts to filter noise to improve ventilator operation are achieved at the expense of lengthening part A.

The time component of the trigger phase is illustrated in the inset of Figure 2. If we consider a perfect pressure-triggered CPAP system of 0 cmH_2O with a set sensitivity of 1 cmH_2O and a slope of 3.4 $cmH_2O/100$ ms (part A), it takes 29 ms for the pressure at the proximal end of the ET tube to decline 1 cmH_2O. Adding 12 ms for the pressure signal travel time means that at least 41 ms must elapse before flow is detected at the circuit Y. Realistic additional delays include 6 ms due to the psol valve response time, an average of 10 ms due to transducer polling (range 0–20 ms), and 3 ms due to an allowable 0.1 cmH_2O error in the pressure transducer, for a total of 19 ms. Assuming random polling, the time interval from onset of inspiratory effort to onset of flow delivery measured at the Y should not exceed 60 ms. Since the measured interval equalled 85 ms (Fig. 2), the remaining 25 ms could not be accounted for. Even if the polling error took the maximum value of 20 ms, a 15 ms of unaccounted delay exists.

Once flow delivery occurs, P_{AWP} remains below atmospheric pressure (Fig. 2). Analysis of P_{AWD} shows a more striking phenomenon. During early inspiration, pressure continues to decline (indicated by the small arrow), then increases gradually toward, but remains below atmospheric pressure throughout inspiration. This pressure decline during inspiration is due to insufficient flow delivery, and is a function of the ventilator flow-pressure control algorithm. The pressure gradient between the circuit pressure due to patient's inspiratory effort and the target pressure is the feedback variable used to control flow and pressure. The target pressure is established by the manufacturer or the set pressure support level when PSV is employed. The larger the pressure gradient, the higher the ventilator delivery of flow. In the PB 7200ae, the flowpressure control algorithm for the pressure-triggered CPAP appears suboptimal. Insufficient flow delivery after the trigger phase, rather than an inadequate ventilator trigger design is the likely primary cause of the increased inspiratory muscle work observed in patients [2]. This contrasts with the older generation of ventilators in which both inadequate ventilator trigger design and insufficient flow delivery account for the increased inspiratory effort [7] and work [8–10]. A measured trigger sensitivity of 6–8 cmH_2O [8–10] and a time delay of 300–700 ms [8] have been reported.

The addition of a humidifier had no effect on the pressure decline after the trigger phase or total PTP (Table 1). The increase in inspiratory circuit resistance (due

Table 1 Total pressure-time product with pressure-triggered, flow-triggered CPAP and pressure-triggered pressure support, with and without a humidifier in the Puritan Bennett 7200ae

PTP, $cmH_2O\cdot s$	PT	FT	PS5
With humidifier	3.97	1.49	0.82
Without humidifier	3.93	1.46	0.78
Changes	0.04	0.03	0.04

Definition of abbreviations: PTP = pressure-time product; PT and FT = pressure-triggered and flow-triggered continuous positive airway pressure (0 cmH_2O), respectively; PS5 = 5 cmH_2O pressure-triggered pressure support

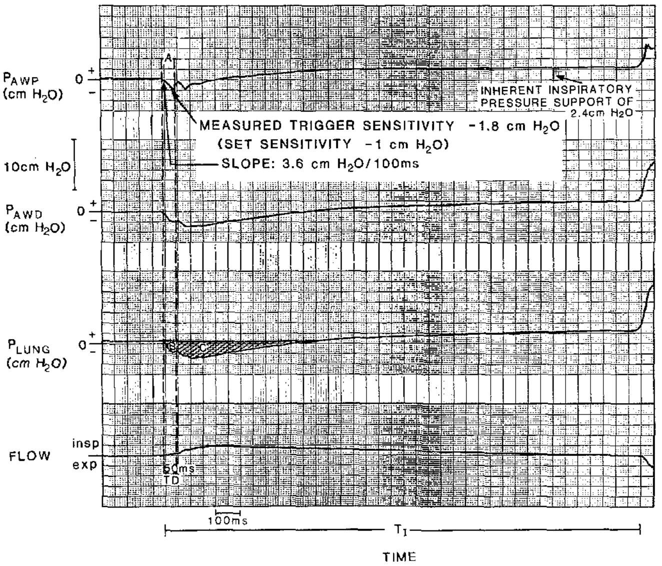

Fig. 5 Pressure-triggered continuous positive airway pressure (0 cmH_2O) of the Siemens SV 300 applied to a mechanical lung model. See Fig. 2 for explanation of *part A, areas B and C*, and definition of abbreviations. Note the inherent inspiratory pressure support early in inspiration. The length of the inspiratory and expiratory circuits provided by the manufacturer was 1.2 m each as compared to 1.8 m used in the Puritan Bennett 7200ae trials. The difference in tubing length accounts for the 4 ms longer in time delay for the Puritan Bennett 7200ae

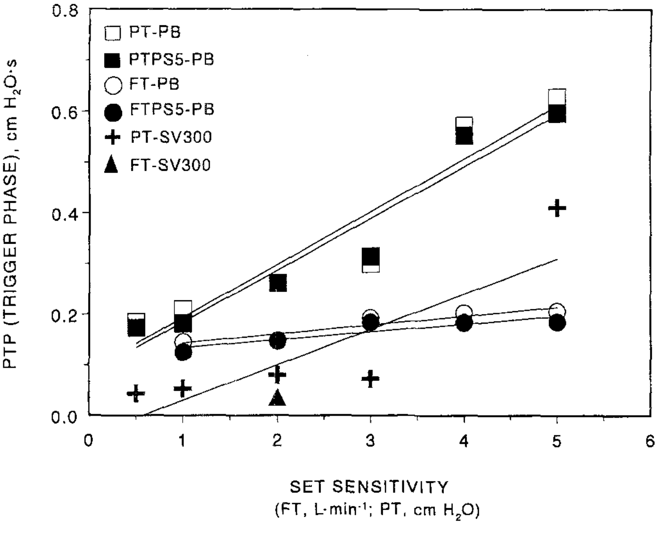

Fig. 6 Relationship between pressure-time product during the trigger phase (trigger PTP, area B, Fig. 2) and set sensitivity with pressure- or flow-triggered continuous positive airway pressure (0 cmH_2O) and 5 cmH_2O pressure support ventilation of the Puritan Bennett 7200ae and Siemens SV 300. Definition of abbreviations: *PT* = pressure-triggered; *FT*, flow-triggered; *PS5*, 5 cmH_2O pressure support; *PB*, Puritan Bennett 7200ae; *SV300*, Siemens SV 300

to the humidifier) if any, results in a greater pressure gradient between circuit and target pressures, and consequently, the greater ventilator delivery of flow. It should be noted that only one type of a wick humidifier was studied. Other types of humidifiers might have a similar effect, however this remains to be determined.

In the microprocessor-based ventilator, the imposed work of breathing due to insufficient flow delivery can be minimized by adjusting flow gain, if available [11], by applying a small amount of pressure support (e.g. 5 cmH_2O) [2], or by sensing circuit pressure at the distal end of the ET tube [12]. The latter two approaches increase the pressure gradient between the circuit and target pressures, hence increasing flow delivery and decreasing inspiratory effort or work.

Since most microprocessor-based ventilators are equipped with PSV, this is probably the simplest way to minimize the inspiratory effort or work imposed by a pressure-triggered CPAP. The effect of a small amount (5 cmH_2O) of pressure support (PB 7200ae) on PTP is illustrated in Fig. 3. Note that the measured trigger sensitivity and the time delay from onset of inspiratory effort to flow delivery are comparable to pressure-triggered CPAP without the application of PSV (Fig. 2). PSV does not reduce the PTP during the trigger phase (trigger PTP or area B, Figs. 2, 3 and 6) or the time delay (Figs. 2, 3 and 7). Instead, it effectively reduces the PTP following the trigger phase (area C, Fig. 3) and total PTP (the sum of area B and C, Figs. 3 and 8a).

Figures 6, 7 and 8a illustrate the relationship between the set trigger sensitivity and trigger PTP, time delay and total PTP, respectively, with and without the addition of

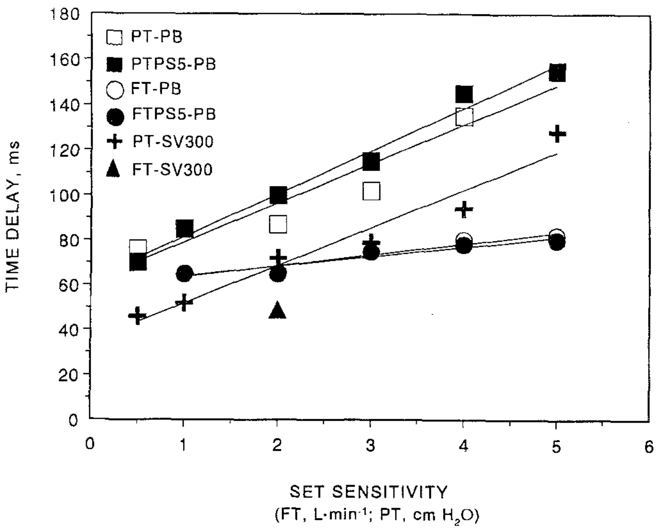

Fig. 7 Relationship between time delay and set sensitivity with pressure- or flow-triggered continuous positive airway pressure (0 cmH_2O) and 5 cmH_2O pressure support ventilation of the Puritan Bennett 7200ae and Siemens SV 300. For definition of abbreviations, see Fig. 6

pressure support. In this trial, pressure support of 5 cmH_2O markedly reduced the total PTP to a level below that with flow-triggered CPAP (PB 7200ae) or comparable to that with pressure-triggered CPAP of the SV300 (see below) (Fig. 8b).

Sensing pressure at the distal end of the ET tube also decreases the work imposed by the pressure-triggered CPAP system [12]. Circuit pressure is lower (more negative) at the distal compared to the proximal end of the ET tube (Fig. 2), because pressure is dissipated in overcoming the resistance of the ET tube. Sensing pressure at the distal end of the ET tube will result in a larger pressure gradient between circuit and target pressure and increase the feedback signal to the pressure-flow control algorithm. Consequently, with a higher flow delivery, there is less inspiratory effort and work than when sensing occurs at the proximal end of the ET tube [12]. However, it should be noted, that both the amount of flow and the rate of flow delivery are important factors to meet the patient's ventilatory demand. Inspiratory work to overcome tube resistance can also be minimized by applying pressure support [13, 14].

When we compared the pressure-triggered CPAP of the PB 7200ae to the SV300, the time delay (Fig. 7) and both trigger and total PTP (Figs. 6 and 8a, respectively) are less with the SV300. This is likely related to i) the short digital polling time of 2 ms and ii) the maintenance of an inherent inspiratory pressure support of 2–3 cmH_2O from early inspiration throughout the inspiratory cycle (Fig. 5). The pressure-triggered CPAP of the SV300 incorporates a base flow of $2 l \cdot min^{-1}$. However, it should be noted that despite providing base flow, a trigger threshold equals to the set pressure sensitivity has to be reached prior to the opening of the inhalation valve. As the subject inhales and the base flow falls to $0 l \cdot min^{-1}$, closure of the exhalation valve allows the pressure within the circuit to decline (as a result of the subject's inspiratory effort) until the trigger threshold is reached. The inhalation valve is then signaled to open, resulting in flow delivery. Total PTP is less with pressure-triggered CPAP of the SV300 compared to that of the PB 7200ae. However, the addition of 5 cmH_2O pressure support to the latter appears to negate the difference (Fig. 8b).

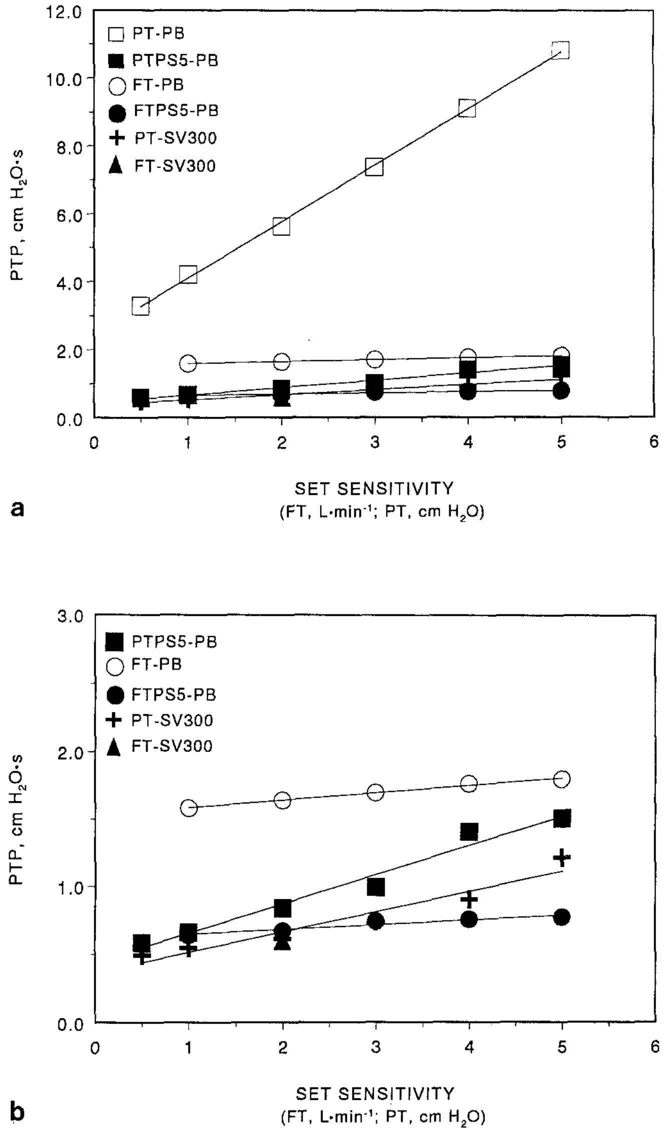

Fig. 8 **a** Relationship between total pressure-time product (the sum of areas B and C, Fig. 2) and set sensitivity with pressure- or flow-triggered continuous positive airway pressure (0 cmH_2O) and 5 cmH_2O pressure support ventilation of the Puritan Bennett 7200ae and Siemens SV300. **b** As in **a** excluding pressure-triggered CPAP of Puritan Bennett 7200ae. Notice the change of range of the Y axis

Flow-triggered spontaneous breath (CPAP)

Flow-triggered CPAP in the PB 7200ae consists of 2 set variables, the base flow and the flow sensitivity. The base flow for adult, can be set between 5 and $20 l \cdot min^{-1}$. The flow sensitivity can be set at a minimum of $1 l \cdot min^{-1}$ to one half of the base flow. In the SV300, for the adult setting, the base flow is automatically set at $2 l \cdot min^{-1}$ while the flow sensitivity can be varied from $0.6 l \cdot min^{-1}$ to a maximum of $2 l \cdot min^{-1}$. The base flow in both ventilators consists of fresh gas that circulates continuously within the inhalation and exhalation circuit, and depending on the base flow value, a slight PEEP might result. In healthy subjects, the degree of base flow does not have a significant effect on inspiratory muscle work [5]. However, preliminary observation in patients recovering from acute respiratory failure, a base flow of $20 l \cdot min^{-1}$ induced a greater inspiratory muscle work compared to that when the base flow was set at $10\,l \cdot min^{-1}$ [15]. The base flow exits through the exhalation port where it is sampled every 20 ms in the PB 7200ae and every 2 ms in the SV 300. The initial demand for flow is satisfied by the base flow, while at the same time, generating the inspiratory flow signal according to the set flow sensitivity. The flow sensitivity is computed as the difference between the base flow and the exhaled flow. In the PB 7200ae, the exhalation valve remains partially open during the trigger phase. After the trigger phase, the exhalation valve may be either partially open or closed, depending on the patient's inspiratory effort. A vigorous inspiratory effort effectively closes the exhalation valve. In the SV 300, the exhalation valve closes completely just prior to flow delivery.

Comparison between flow- and pressure-triggered CPAP of the PB 7200ae (Table 2)

During the trigger phase, flow-triggered CPAP (Fig. 4) is characterized by a relatively smaller pressure decline compared to that of pressure-triggered CPAP. With flow-triggered CPAP, shortly after the trigger phase, P_{AWP} gradually increases to above atmospheric pressure throughout inspiration (Fig. 4). However, similar to pressure-triggered CPAP (Fig. 2), the analysis of P_{AWD} shows an initial decline in pressure after triggering is completed, although to a lesser extent (Fig. 4, indicated by the small arrow). The addition of 5 cmH_2O pressure support to flow-triggered CPAP also decreases total PTP (Fig. 8a). This effect is primarily discernible after the trigger phase. However, unlike with the pressure-triggered CPAP, the addition of 5 cmH_2O pressure support to flow-triggered CPAP in decreasing the total PTP is probably of questionable significance (Fig. 8a and b).

Comparison between flow- and pressure-triggered CPAP of the SV 300 (Table 3)

As mentioned above, we only evaluated a flow sensitivity of $2\,l \cdot min^{-1}$, since a sensitivity of less than $2\,l \cdot min^{-1}$ can only be arbitrarily set. Compared with the 1 cmH_2O pressure sensitivity commonly used in clinical practice, the effects of both flow- and pressure-triggering on time delay (Fig. 7), trigger PTP (Fig. 6) and total PTP (Fig. 8b) are practically identical. It is possible that the lack of differences in time delay and trigger PTP between flow- and pressure-triggering is a function of the flow waveform of the simulated lung. In this study, we employed the ramp flow waveform. With the sine flow waveform, time delay is longer and trigger PTP is larger with the pressure- than with the flow-triggered CPAP (unpublished observation). After the trigger phase, the relatively sufficient flow delivery with both flow- and pressure-triggering results in nearly identical total PTP.

Comparison between flow-triggered CPAP of the SV 300 and the PB 7200ae

For a given flow sensitivity of $2\,l \cdot min^{-1}$, both trigger PTP (Fig. 6) and total PTP (Fig. 8b) are less with the SV 300. During the trigger phase, the smaller PTP value with the SV 300 is primarily related to the shorter time delay (50 ms versus 65 ms with the PB 7200ae), since changes in P_{LUNG} from onset of inspiratory effort to onset of flow delivery are essentially similar (2.2 cmH_2O in the SV 300 versus 2.5 cmH_2O in the PB 7200ae). The short digital polling time of 2 ms versus 20 ms with the PB 7200ae partly accounts for the difference in the time delay.

The lower total PTP with the flow-triggered SV 300 compared to the PB 7200ae is likely due to the superior flow-pressure control algorithm of the former. Figure 8b shows that the application of 5 cmH_2O pressure support

Table 2 Characteristics of pressure- and flow-triggered CPAP of the Puritan Bennett 7200ae

	Pressure triggering	Flow triggering
Set sensitivity	Pressure	Flow; range $1\,l \cdot min^{-1}$ to one half of the base flow
Trigger phase:		
Exhalation valve	Closed	Open
Digital polling time	20 ms	20 ms
Inspiratory flow	Negligible due to circuit compliance	Provided by the base flow, adjustable between $5-20\,l \cdot min^{-1}$
Time delay	Relatively long	Relatively short
Post-triggering:		
Exhalation valve	Closed	Open or closed depending on patient effort
Feedback signal for flow-pressure control	Circuit pressure	Circuit pressure
Target pressure for flow-pressure control	Below end-expiratory pressure, resulting in under delivery of flow	0.5 – 1 cmH_2O above end-expiratory pressure, hence the relatively sufficient flow delivery

Table 3 Characteristics of pressure- and flow-triggered CPAP of the Siemens SV300

	Pressure triggering	Flow triggering
Set sensitivity	Pressure	Flow; range $0.6-2\,l\cdot min^{-1}$
Trigger phase:		
Exhalation valve	Closes when base flow falls to $0\,l\cdot min^{-1}$	Open
Digital polling time	2 ms	2 ms
Inspiratory flow	Initially provided by the base flow of $2\,l\cdot min^{-1}$	Provided by the base flow, a fixed value of $2\,l\cdot min^{-1}$
Time delay	Relatively short	Relatively short
Post-triggering:		
Exhalation valve	Closed	Closed
Feedback signal for flow-pressure control	Circuit pressure	Circuit pressure
Target pressure for flow-pressure control	Inherent pressure support ($2-3$ cmH_2O) above end-expiratory pressure, hence relatively sufficient flow delivery	Similar as in pressure-triggering

to the PB 7200ae flow-triggered CPAP reduces total PTP similar to that of the SV300, supporting the contention that the flow-pressure control algorithm of the SV300 is superior to that of the PB 7200ae. This is likely related to differences in the pressure gradients (between the circuit and target pressures) that are the feedback signals for the flow-pressure control algorithm. In the SV300, the target pressure is an inherent pressure support level of $2-3$ cmH_2O, while in the flow-triggered PB 7200ae, the target pressure is $0.5-1.0$ cmH_2O above end-expiratory airway pressure. Therefore, the flow-triggered CPAP of the SV300 provides a greater feedback signal than the PB 7200ae. The clinical significance of the difference between flow-triggered CPAP of these two ventilators on patient inspiratory muscle work (W_I), if any, remains to be determined.

Because of the fixed low base flow in the flow-triggered CPAP of the SV300, depending on the set flow sensitivity, the presence of a circuit leak is apt to induce auto-cycling. Under this condition, switching to a pressure-triggered CPAP will correct the auto-cycling while attempting to assess the circumstance.

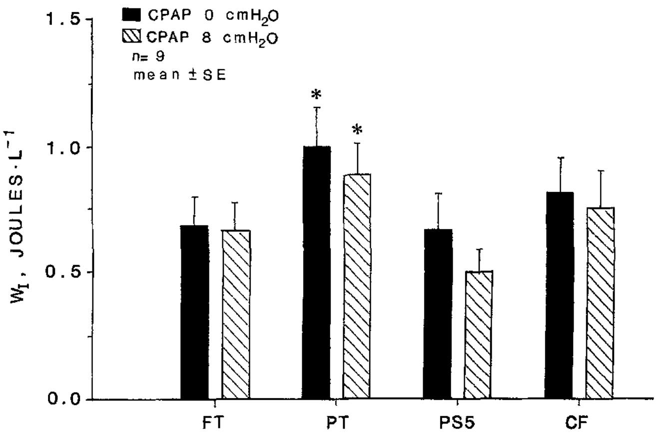

Fig. 9 Inspiratory muscle work of breathing (W_I, Joules$\cdot l^{-1}$) with flow-triggered (*FT*), pressure-triggered (*PT*), 5 cmH_2O pressure support ventilation (*PS5*) and continuous flow (*CF*) continuous positive airway pressure (*CPAP*) at 0 (*solid bars*) and 8 cmH_2O (*hatched bars*) of the Puritan Bennett 7200a. With FT CPAP, base flow was $10\,l\cdot min^{-1}$ and flow sensitivity was $2\,l\cdot min^{-1}$; with PT CPAP and PS5, pressure sensitivity was -1 cmH_2O. $*p<0.01$ PT versus FT and PS5 (CPAP 0); PT versus PS5 (CPAP 8). Adapted from [2] with permission

Effect of pressure- and flow-triggered CPAP on inspiratory muscle work

Previous studies of intubated patients have shown that the CPAP systems influence the patients' W_I [16, 17]. Currently, comparison on the effect of pressure- and flow-triggered CPAP on patient W_I is available only with the PB 7200a [2]. From the above analysis, it is expected that W_I with pressure-triggered CPAP is significantly higher than that with flow-triggered CPAP. This has been demonstrated in both healthy subjects [5] and, in intubated patients (Fig. 9) [2]. In those studies [2, 5], W_I was estimated using the esophageal balloon catheter and calculated using the Campbell's diagram [18]. Since most microprocessor-based ventilators are equipped with PSV, the disadvantages encountered with pressure-triggered CPAP can be overcome in the clinical setting, by adding a small amount (5 cmH_2O) of pressure support. As shown in Figure 9, at the levels of CPAP studied, W_I (Joules$\cdot l^{-1}$) with pressure-triggered CPAP is greater than with flow-triggered CPAP. Pressure support of 5 cmH_2O reduces W_I to a level comparable with that of flow-triggered CPAP.

Pressure- and flow-triggered mandatory breaths

Most microprocessor-based ventilators employ pressure-triggering for AC, SIMV and PSV. As mentioned above, flow-triggering is now available for all modes of ventilation in both the PB 7200ae and SV 300. During the trigger phase, the generation of pressure or flow signals for fresh gas delivery of pressure- or flow-triggered mandatory breaths, respectively, operate in a fashion similar to that of the spontaneous breaths (CPAP). For mandatory breaths, following the trigger phase, alteration of peak inspiratory flow rate [19–21] with AC or SIMV, and adjustment of initial flow delivery [22, 23] during PSV, remain essential elements in meeting the patient's early demand for flow and determining W_I.

Our preliminary result with SIMV (PB 7200a) demonstrates that W_I of the mandatory breaths does not differ significantly between flow-triggered and pressure-triggered SIMV [3]. We employed a square flow waveform at a rate of $60\,l \cdot min^{-1}$ for both pressure- and flow-triggered SIMV. On the other hand, W_I of the spontaneous breaths was greater with pressure-triggered than with flow-triggered SIMV, particularly at the low SIMV support level. Our results support the premise that the increased W_I with the pressure-triggered CPAP is primarily related to the insufficient flow delivery after the trigger phase rather than events during the trigger phase. Differences within the trigger phase, if present, these are probably small and of questionable clinical significance.

Summary

Currently, the PB 7200ae and SV300 incorporate both pressure- and flow-triggered spontaneous (CPAP) and mandatory breaths. Using a mechanical lung model, the PB 7200ae flow-triggered CPAP appears superior to its pressure-triggered CPAP. This is due to the insufficient flow delivery of the pressure-triggered CPAP. The addition of 5 cmH_2O pressure support to the pressure-triggered CPAP results in a total PTP less than that with the flow-triggered CPAP.

The pressure- and flow-triggered CPAP of the SV 300 are comparable with respect to the effects on time delay, trigger and total PTP. The effect on time delay and trigger PTP is perhaps a function of the flow waveform of the lung model. Flow delivery is sufficient and comparable with both pressure- and flow-triggered CPAP.

Differences on the effect on total PTP between pressure- or flow-triggered CPAP of the PB 7200ae and the SV 300 are primarily related to the short time delay during the trigger phase and relatively sufficient flow delivery of the latter. The application of pressure- or flow-triggered pressure support of 5 cmH_2O in the PB 7200ae practically eliminates the differences.

The data presented in this review are based on trials in a mechanical lung model. Data in patients are limited, however, the work of breathing with flow-triggered CPAP of the PB 7200ae is significantly less than that with its pressure-triggered CPAP. The application of 5 cmH_2O pressure support is sufficient to overcome the work imposed by pressure-triggered CPAP. To our knowledge, a comparison on the work of breathing with flow-triggered CPAP of the SV 300 and PB 7200ae in the patients and its clinical significance, if any, are not available and remains to be determined.

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