Effects of Different Pressure Support Termination on Patient-Ventilator Synchrony

Yoshitsugu Yamada MD and Hong-Lin Du MD

BACKGROUND: In pressure support ventilation (PSV), ventilators terminate their flow when the inspiratory flow decays to a certain flow (flow criteria) or when the airway pressure rises a certain amount above the set pressure support level (pressure criteria). There are significant differences among intensive care unit ventilators in regard to these termination criteria. PURPOSE: In this adult simulation study, we investigated if the termination criteria used in intensive care unit ventilators affect the 1patient-ventilator synchrony in the transition to exhalation. METHODS: A two-compartment lung model was used to simulate spontaneous breathing of the patient with high demand (peak flow of 60 L/min) or low demand (peak flow of 30 L/min). Three ventilators with different flow criteria and pressure criteria in the inspiratory termination were alternately attached to the test lung: the Nellcor Puritan Bennett 7200ae (NPB7200ae), the Siemens Servo300 (SV300), and the Newport Wave E200 (E200). During testing, the PSV level was set at 10 cm H_2O with positive end-expiratory pressure of 0 or 5 cm H_2O. The termination delay time, termination type, inspiratory muscle work, plateau and peak inspiratory pressures, and inspiratory area percent were measured. The tests were conducted at the compliance of 20, 40, and 80 mL/cm H_2O, with a resistor of R5 or R20. RESULTS: In most of the experimental settings, all three ventilators terminated their flow within 0.1 second before or after the end of the 'patient' inspiratory effort. In the 'patient' with long time constant, termination criteria in the SV300 delayed the inspiratory termination by 0.5 second. In all settings in the NPB7200ae and some settings in the E200, the ventilator flow was terminated by the pressure criteria, not by the flow criteria. The NPB7200ae showed pressure undershoot during the first half of the inspiration and required the highest patient work in all settings, especially at high patient demand. In the SV300, the actual support level was higher than the set level. Its peak inspiratory airway pressure was also the highest among the three ventilators. There was a trigger dyssynchrony in the E200 at high demand with high resistance/high compliance. CONCLUSION: In most settings, the termination criteria used in PSV in the three ventilators provided a relatively reasonable patient-ventilator synchrony in the transition to exhalation. The marked delay in the ventilator inspiratory termination may occur under the conditions of long time constant with low demand in the SV300, which resulted mainly from the combination of the inappropriate pressure criteria and flow criteria. [Respir Care 1998;43(12):1048–1057] *Key words: mechanical ventilation, pressure support, work of breathing, ventilators, patient-ventilator synchrony.*

Background

Pressure support ventilation (PSV) has been one of the most frequently applied modes. There are several factors that determine the performance of PSV: ventilator trigger response, pressure rise rate (or slope) upon trigger, and ventilator inspiratory termination timing.[1] Studies on the ventilator trigger response and the pressure rise rate in PSV have clearly shown the importance of their roles in decreasing the patient work of breathing and improving

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patient-ventilator synchrony.[2–6] It has been suggested[7] that ventilator inspiratory termination may also be important: Premature termination may increase inspiratory muscle work, and delayed termination may increase the load on expiratory muscles. In a lung model study, Bunburaphong et al[8] evaluated expiratory delay time in nine noninvasive pressure ventilators together with one intensive care unit (ICU) ventilator. They demonstrated that there were great differences in the termination delay time among the noninvasive pressure ventilators. With regard to ICU ventilators, MacIntyre and Ho[4] evaluated the termination criteria at 25% and 50% of peak flow and found that changing termination criteria in PSV from 50% to 25% of peak flow had minimal effect on the ventilatory pattern or patient-ventilator synchrony in clinically stable patients using a modified BEAR-3 ventilator.*

There are two primary methods to terminate the ventilator flow delivery in ICU ventilators during PSV: flow criterion and pressure criterion. As regards the flow or pressure level at which the ventilator flow is terminated, significant differences exist among ICU ventilator manufacturers and even among different model ventilators of the same manufacturer.[9,10] By flow criteria, ventilator flow will be terminated when the inspiratory flow has decayed to a certain flow. This flow can be either a fixed absolute flow (eg, 5 L/min in the Nellcor Puritan Bennett 7200 and 4 L/min in the Infrasonics Adult Star), a fixed rate based on the peak inspiratory flow (eg, 5% of peak inspiratory flow in the Siemens Servo300 and 25% of peak inspiratory flow in the Siemens Servo 900 and Bird 8400ST), or variable termination flow based on both peak inspiratory flow and the elapsed inspiratory time (T_I) (such as in the Newport Wave E200). By pressure criteria, the ventilator flow is terminated when the airway pressure rises a certain amount above the set pressure support level. This pressure criteria above the set pressure level can be +1.5 cm H_2O (in the Nellcor Puritan Bennett 7200 [NPB7200ae]), +2.0 cm H_2O (in the Newport Wave E200 [E200]), +3.0 cm H_2O (in the Siemens Servo 900), or +20 cm H_2O (in the Siemens Servo300 [SV300]). Until now, there has been no objective evidence as to whether these different termination criteria affect the patient-ventilator synchrony. Moreover, it also was not known if the patient-ventilator synchrony using each termination criterion was affected by patient characteristics, because patient mechanics (eg, resistance and compliance) may exert influence on the airway flow change during the inspiratory phase.

*Suppliers of commercial products are identified in the Product Sources section at the end of the text.

Purpose

The purpose of this study was to investigate, under different combinations of respiratory resistance and compliance, whether the termination criteria used by ICU ventilators affect the patient-ventilator synchrony in the transition to exhalation in an adult lung model. The patient-ventilator synchrony was evaluated by the termination delay time (ie, time from the end of the 'patient' inspiratory effort to the end of ventilator inspiratory flow). Since the termination of the inspiration may be affected by a ventilator's control of the flow delivery during inspiration with the same termination criteria, the performance characteristics of the ventilators during the inspiratory phase were evaluated as well. The NPB7200ae, the SV300, and the E200 were used to represent ventilators with different termination criteria.

Methods

Model

Spontaneous breathing was simulated using a two-compartment mechanical lung model (Michigan, TTL model 1600) (Fig. 1). The left side of the lung model was connected to the tested ventilator; the right side was connected to and driven by a BEAR-5 ventilator using a sinusoidal flow wave pattern. The model in this study differs from that used by other researchers,[11,12] in that it used a metal connector to completely connect both sides of the model. This connection allowed the two compartments to behave like compliances in series. Because of this connection, if the flow termination of the tested ventilator comes after the end of the inspiration of the driving lung, the elastic recoil force from the driving lung impacts the tested lung and causes an airway pressure elevation. This model simulates the interactive relationship between a ventilator and a patient who does not exhibit active expiratory effort. When the compliance of the driving side lung is set to the chest wall compliance, the pressure in the driving side lung during the driving phase can be taken as the inspiratory muscle pressure. The integration of the volume change and pressure change during the driving phase is taken as the work of inspiratory muscles (Wmus).[13,14] After the driving phase, the pressure or flow information of the driving side in this model cannot be used for analysis of the Wmus because the driving compartment at this time communicates with the atmosphere through the open exhalation valve of the driving ventilator.

Setup

The compliance of the driving lung was set at 200 mL/cm H_2O to simulate chest wall compliance. A hot wire flow transducer (Minato, Model RF-L) and a pressure trans-

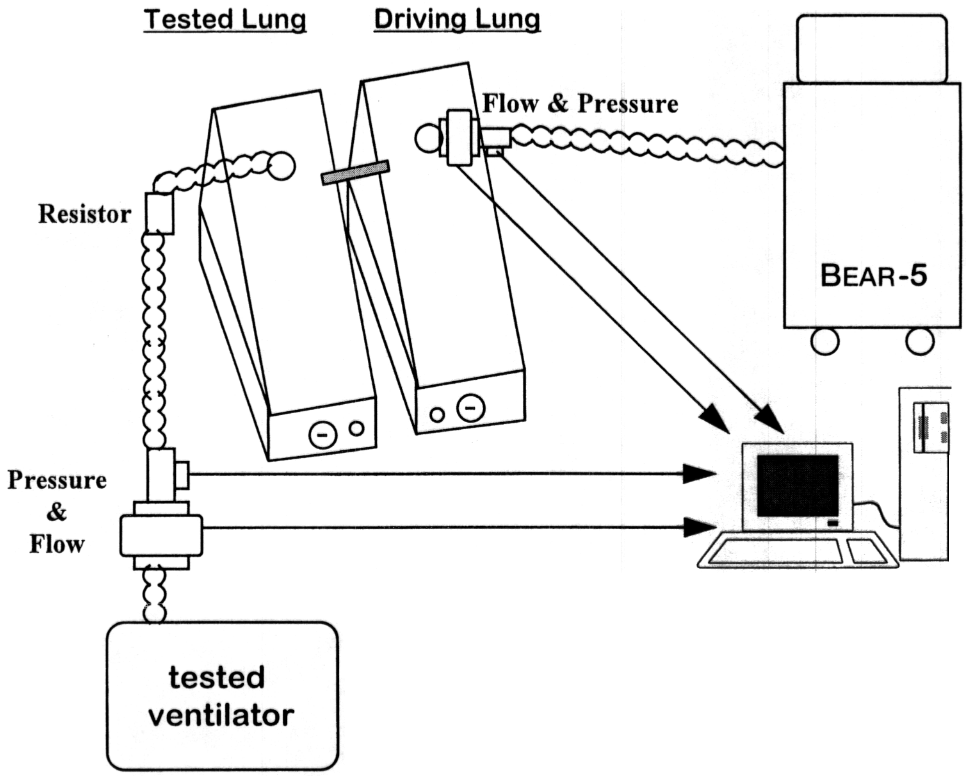

Fig. 1. Schematic representation of the lung model.

ducer (Heise, 901A) were connected to the inlet of the driving lung. The left lung (tested lung) was connected to each of the tested ventilators through a standard adult breathing circuit with no humidifier attached (circuit compliance = 0.98 mL/cm H_2O). The pressure and flow at the airway opening were measured by the same types of transducers that were used at the driving side. The signals of pressure and flow transducers at both the driving side and tested side were digitized at 100 Hz and recorded on a computer recorder (Data Translation, DT2831). To simulate the respiratory system resistance, a parabolic resistor of R5 or R20 was placed between the tested lung and the breathing circuit. The compliance of the tested lung was adjusted to 20, 40, or 80 (C20, C40, or C80) mL/cm H_2O. With the T_I set to 1.0 second, the peak flow of the BEAR-5 ventilator was adjusted to provide the peak inspiratory flow of 30 L/min and 60 L/min at the airway opening of the tested side when the tested lung was not connected to a ventilator. These flow rates simulated low and high patient inspiratory efforts. During the evaluation of the tested ventilators, the 3 tested ventilators set in the spontaneous mode were connected to the tested lung alternately. The positive end-expiratory pressure (PEEP) was set at 0 or 5 cm H_2O and pressure support was set at 10 cm H_2O. Pressure trigger of -0.5 cm H_2O was used in all 3 ventilators. In the SV300, the inspiratory rise time was adjusted to 1%. In the E200, the bias flow was set at 5 L/min, as recommended by its operating manual.[15] The 4 transducers used in the study (2 for pressure and 2 for flow) were calibrated immediately before the experiment with a calibration analyzer (Allied Healthcare Products, RT200).

Measurements and Data Analysis

The following parameters were measured from the computer records: termination delay time and termination type, Wmus expressed as J/L during the driving phase at the driving side, plateau and peak inspiratory pressures at the tested side, and inspiratory area percent (Area-I%) of the pressure at the tested side.

The termination delay time was defined as the time between the end of the inspiration of the BEAR-5 and the return of the inspiratory flow of the tested ventilator to zero (Fig. 2). The end of the inspiration of the BEAR-5 was calculated as follows: The inspiratory onset of the BEAR-5 during each test was read from the flow waveform of the driving compartment; the T_I of the BEAR-5 was measured from the flow waveform of the driving compartment when no tested ventilator was attached to the tested lung compartment (the variation of the T_I of the BEAR-5 was confirmed to be $\leq$ 20 millisecond in all experimental settings in the preliminary experiments); and timing of the end of the inspiration of the BEAR-5 when a tested ventilator was being evaluated was then BEAR-5's inspiratory onset tim-

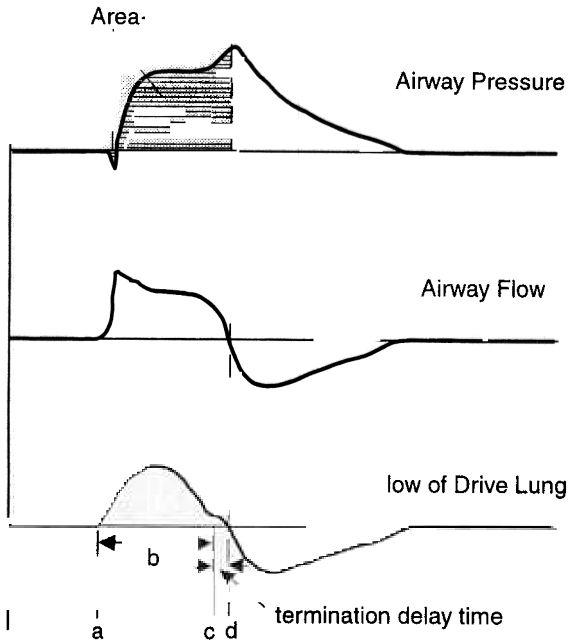

Fig. 2. Calculations of the termination delay time and the inspiratory area percent of airway pressure. The termination delay is defined as the time between the end of the inspiration of the drive ventilator (c) and the return of the inspiratory flow of the tested ventilator to zero (d). The mandatory inspiration of the drive ventilator starts at "a" and lasts for the duration of "b," which is taken when no ventilator is connected to the tested lung. The inspiratory area percent of airway pressure is the ratio of the line-shaded areas (Area-I, the areas of the pressure-time tracing above and below baseline during the inspiration) to the dot-shaded rectangle area (ideal area).

ing plus BEAR-5's T_I. To identify whether the ventilator flow was terminated by the flow criterion or pressure criterion, the time point when the airway pressure at the tested side reached the pressure criterion level was read. The pressure criterion level was taken as 11.5 cm H_2O above PEEP in the NPB7200ae, 30.0 cm H_2O above PEEP in the SV300, and 12.0 cm H_2O above PEEP in the E200.[9,10,15] The patient airway flow at this time point was measured and compared with the flow criterion. If it was higher than the flow criterion, the inspiration was thought to be terminated by the pressure criterion; otherwise, the inspiration was considered to be terminated by the flow criterion. The inspiration was always considered to be terminated by the flow criterion if the airway pressure never reached the pressure criterion level during inspiration.

The Wmus was calculated as the integral of the pressure at the driving side with regard to the volume at the tested side during the driving phase. The volume at the tested side was obtained by integrating the flow signal of the tested side over time. The intention of using the volume at the tested side (instead of using the volume at the driving side) in the calculation of the Wmus was to simulate a clinical situation and to eliminate the effect of the compressed volume in the model. The plateau inspiratory airway pressure at the tested side was read if the airway pressure did not change 0.5 cm H_2O within a 150-millisecond period during the inspiratory phase. The Area-I% was calculated using the method introduced by Bunburaphong et al.[8] The Area-I% was the ratio of the area of the pressure-time tracing above and below baseline during the driving phase at the tested side to the ideal area (Fig. 2). The ideal area was defined as the rectangle created by T_I and the maximal pressure at the tested side above the baseline pressure.

All pressure values in this study are presented as values above PEEP. Three breaths were analyzed for each experimental setting after a 2-min stabilization period. Because all parameters among the three breaths showed negligible variation, only mean values are presented in this report.

Results

Ventilator Inspiratory Termination (Table 1)

All three ventilators terminated their flow delivery within 0.1 second before or after 'patient'-stopped inspiratory effort in most experimental settings. The termination was delayed by 0.5 seconds in the SV300 in the 'patient' with long time constant (R20, C80) and low inspiratory effort (peak inspiratory flow = 30 L/min) (Fig. 3). The inspiration in the NPB7200ae was always terminated by its pressure criterion, while inspiration was terminated by the flow criterion in the SV300. In the E200, if the 'patient' demand was low, inspiration was terminated by its flow criterion, but it was terminated either by its flow criterion or by its pressure criterion in the high-demand 'patient.' The termination delay is not consistently affected by PEEP; however, administration of PEEP slightly prolonged the termination delay time when airway resistance was high (R20) in most of the settings in all ventilators.

The Work of the Inspiratory Muscles (Table 2)

The Wmus in the NPB7200ae was always higher than that in the other 2 ventilators. The Wmus in the SV300 was the lowest among the 3 ventilators, although the differences between the SV300 and the E200 were negligible.

Plateau Inspiratory Pressure, Peak Inspiratory Pressure, and Inspiratory Area Percent (Tables 3–5)

The NPB7200ae consistently displayed an undershoot of airway pressure during the first half of inspiration, especially in high-demand conditions (peak inspiratory flow = 60 L/min) (Figs. 3 & 4). The significant pressure undershoot waveform in high-demand conditions in the NPB7200ae did not allow a stable plateau pressure segment

Table Termination Delay Time (in Seconds) for Three Pressure Support Ventilators Set at Positive End-Expiratory Pressure of 0 or 5 cm H_2O (PEEP-0 or PEEP-5) and Tested at Compliance of 20, 40, or 80 (C20, C40, C80) and Parabolic Resistance of 5 or 20 (R5, R20).

	High Demand (60 L/min)			Low Demand (30 L/min)		
	NPB7200	SV300	E200	NPB7200	SV300	E2(
PEEP-0						
R5, C80	0.05(P)	0.09	0.04(P)	0.02(I	0.06	0.05
R5, C40	0.03(P)	0.05	0.01	0.02(I	0.01	0.06
R5, C20	−0.04(P)	0.01	0.01	0.03(I	0.07	0.02
R20, C80	0.06(P)	0.10	0.05(P)	0.07(I	0.56	0.02
R20, C40	0.07(P)	0.10	0.09(P)	0.07(I		0.00
R20, C20	0.04(P)	0.05	0.04	0.03(I	0.04	0.01
PEEP-5						
R5, C80	0.00(P)	0.06	0.04	0.01(P)	0.09	0.04
R5, C40	0.03(P)	0.05	0.00	0.00(P)	0.08	0.02
R5, C20	0.04(P)	0.04	0.03	0.03(P)	0.02	0.04
R20, C80	0.14(P)	0.19	0.11(P)	0.04(P)	0.57	0.04
R20, C40	0.10(P)	0.13	0.09(P)	0.04(P)		0.02
R20, C20	0.05(P)	0.08	0.05	0.06(P)	0.07	0.02

A two-compartment lung model was used to simulate spontaneous breathing of patients with high- or low-demand peak flow. Positive represent delayed termination time: negative values represent premature termination time. Termination was pressure-activated (indicate flow-activated. See Methods for details. Ventilators: Nellcor Puritan Bennett 7200ae (NPB7200), Siemens 300 (SV300), Newport Wa

meeting our plateau pressure definition. When comparing the plateau inspiratory pressure with the target pressure level (10 cm H_2O above PEEP), the plateau pressure was 1–2 cm H_2O lower in the NPB7200ae and 1–2 cm H_2O higher in the SV300 than the target pressure. The undershoot airway pressure in the NPB7200ae also resulted in the lowest Area-I % among the 3 ventilators. In the condition of high demand (peak inspiratory flow = 60 L/min) with long time constant (R20, C80), the E200 showed a double-cycled pressure waveform because of the initial pressure overshoot (Fig. 4). This double-cycled waveform caused a low Area-I% in this condition in the E200. Similar to the differences of plateau pressure among the three ventilators, the peak inspiratory airway pressure was always the highest in the SV300, followed by the E200 and then the NPB7200ae. The peak inspiratory pressure became elevated as the resistance increased and the compliance decreased. It was as high as 12 cm H_2O above the target pressure in R20, C20 with high-demand condition in the SV300.

Discussion

Our results demonstrated that in most of the experimental settings, all 3 ventilators that we tested terminated their flow in PSV within 0.1 second before or after the end of the 'patient' inspiratory effort, suggesting a relatively reasonable patient-ventilator synchrony in the transition to exhalation. In the low-demand 'patient' with long time constant (R20, C80), termination criteria in the SV300 delayed the ventilator inspiratory termination by 0.5 seconds (Table 1, Fig. 3). In all settings in the NPB7200ae and in some settings in the E200, inspiration was terminated by the pressure criteria instead of flow criteria.

In order for airway pressure to remain at the target level during the inspiration of PSV, ventilators decrease their flow as the patient effort decreases. With an ideal pressure control system, in order to maintain the target pressure level, the ventilator flow would be 0 when the patient completely stops his effort. Therefore, the flow criterion of the inspiratory termination in an ideal pressure control system would be set close to 0 L/min. In reality, however, there are inherent delays in the pressure control feedback loop, and the pressure control algorithm more or less lacks precision in all ventilators. As a result, in order to terminate their flow to synchronize with the patient, commercial ventilators are designed to have a termination flow of slightly higher than 0 L/min. The ventilators are designed to terminate their flow when the inspiratory flow drops to either a fixed flow (eg, 5 L/min in the NPB7200ae), a percentage of the peak delivered flow (eg, 5% in the SV300), or a variable termination flow (eg, in the E200).

In addition to termination of flow according to these flow criteria, the ventilators also terminate their flow by the pressure criteria (ie, when airway pressure reaches 1.5 cm H_2O above the target pressure level in the NPB7200ae, 20 cm H_2O above the target pressure level in the SV300,

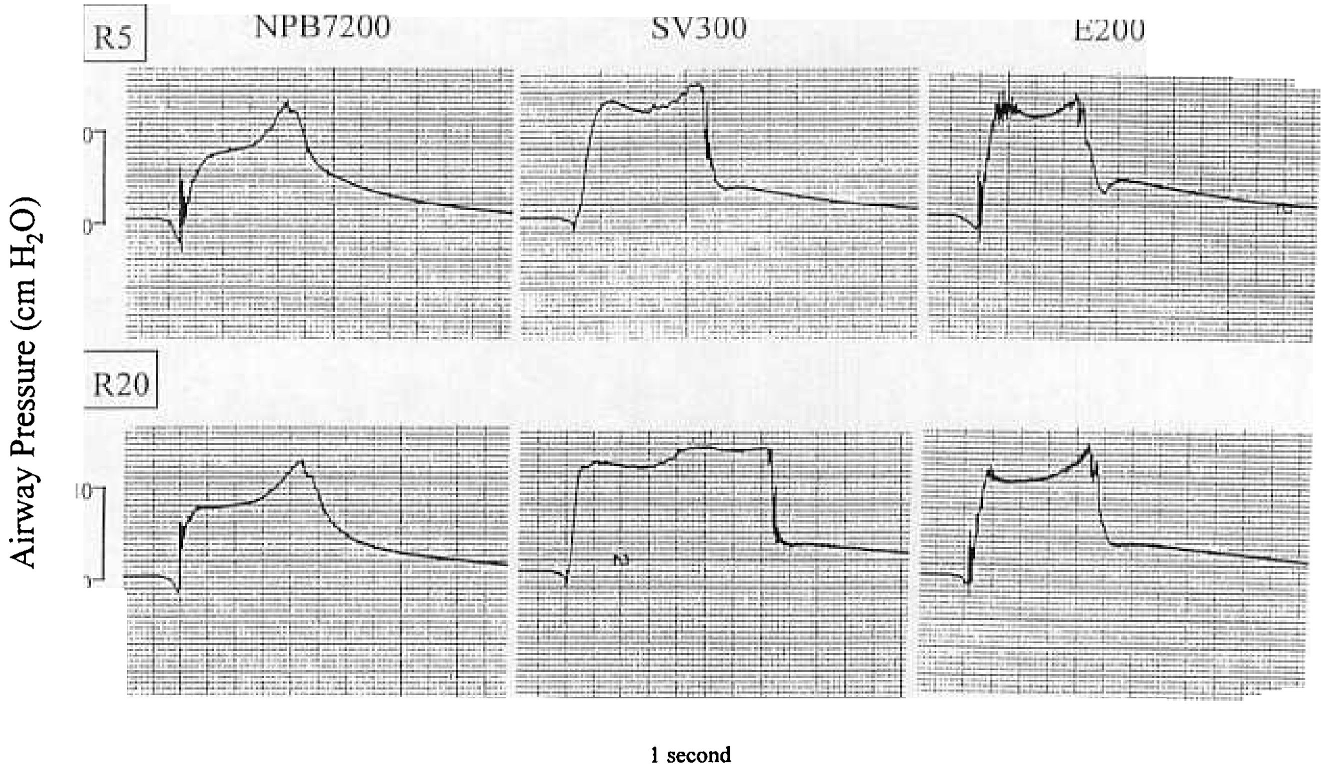

Fig. 3. The pressure waveforms in low demand. Patient demand: 30 L/min; compliance: 80 mL/cm H_2O; resistance: R5 (upper) ɿd R2((lower). NPB7200 = Nellcor Puritan Bennett 7200ae; SV300 = Servo 300; E200 = Wave E200.

or 2.0 cm H_2O above the target pressure level in the E200). These pressure criteria serve as a backup measure to the flow criteria. The results in our study showed that the pressure criteria in the SV300 (20 cm H_2O above the target pressure) did not activate termination in any setting: The ventilator flow was terminated by the flow criterion. This may partly explain why the peak inspiratory airway pressure in the SV300 can be as high as 12 cm H_2O above the target pressure (Table 4). The fact that inspiration in the NPB7200ae was always terminated by the pressure criterion suggests that the flow criterion of 5 L/min used in the NPB7200ae is not high enough to terminate its flow at the proper time at the applied settings. In other words, the flow criterion of 5 L/min in the NPB7200ae has not functioned in the ventilator inspiratory termination. Because the termination in the NPB7200ae was not markedly delayed even though the ventilator flow was always terminated by the pressure criterion, it can be inferred that the pressure criterion in the SV300 is the major reason for the significant termination delay that occurred in the SV300. The termination delay in the SV300 may also be attributed to the lower flow criterion because the highest peak flow recorded in the SV300 study was 76 L/min (which was converted to 3.8 L/min of flow criterion in ventilator inspiratory termination).

In the E200, ventilator flow was terminated by the flow criteria without significant delay or prematurely in low-demand conditions. This indicates that relating the flow criteria with the elapsed T_I in addition to peak flow may result in better patient-ventilator synchrony than using only peak flow. In the E200, termination is based on the following equation: termination flow = $(\alpha + \beta \times TI) \times PF^{\gamma}$, where TI is the elapsed T_I from the onset of the ventilator flow, PF is the peak inspiratory flow, and α, β, and γ are constants.† With this flow criterion, the longer the elapsed T_I, the higher the termination flow criteria, and vice versa. This might compensate the slower decay of the inspiratory flow at long time constant and low demand. In the high demand, this compensation with the elapsed T_I is not enough, as demonstrated by the pressure-cycled breath at high demand and high resistance in the E200.

Jubran and co-workers have studied the effect of PSV in chronic obstructive pulmonary disease patients.[16] In their study, they ventilated chronic obstructive pulmonary disease patients with PSV by use of the Servo 900C ventilator. As a result, the patients with higher time constants displayed lower bounds of expiratory pressure time prod-

†Personal communication, Cyndy Miller RI lewport Medic Instruments Inc, Costa Mesa CA.

Tabl Inspiratory Muscle Work (in J/L) for Three Pressure ntilators Set at Positive End Expiratory Pressure of 0 or 5 cm H_2O (PEEP-0 or P Tested at Compliance of 20 or 80 (C20, C40, C80) and Parabolic Resistance of 5 (R5, R2(

	High Demand (60 L/min)			Demand (30		
	NPB7200	SV300	200	NPB7200	SV300	0
PE						
R5, C80			0.89		0.05	
R5, C40			1.32	46	0.25	
R5, C20	3.0	2.78	2.88	37		
R20, C80	2.6	2.33	2.63		0.30	
R20, C40	3.1		3.10		0.55	
R20, C20			3.61		1.48	
EEP-5						
R5, C80		0.68	0.64		0.02	
R5, C40		1.09	1.06		0.18	
R5, C20		2.61	2.61			
R20, C80		2.51	2.71	0.37		
R20, C40	2.95	2.85	2.90	0.54		
R20, C20	3.61	3.46		1.38		

model was used to simulate spontaneous breathi 200ae (NPB7200), Siemens 300 (SV300), Newp

uct before the cessation of the inspiratory flow, suggesting expiratory muscle recruitment while the ventilator was still inflating the thorax. Because the Servo900C utilizes a flow criterion of 25% of the peak flow and a pressure criterion of 3 cm H_2O,[9,10] the ventilator inspiratory termination should be earlier using the Servo900C than the SV300. This means that the expiratory muscle work would be higher if the SV300 was used in these patients. The significant delay in the ventilator inspiratory termination will also shorten expiratory time and may exacerbate auto-PEEP, which frequently is an important clinical issue in these patients.[17]

In addition to the flow criterion and pressure criterion, ICU ventilators also have a termination criterion based on maximum T_I in order to protect patients in case of a massive circuit leak. The ventilators will terminate their flow if the T_I reaches 3.0 seconds in the NPB7200ae and the E200 or 80% of one breath interval in the SV300.[9,10,15] Because there were no patient circuit leaks during this study, there were no breaths that lasted long enough to be terminated by this criterion.

Some newly released ICU ventilators (eg, NPB 840, Hamilton Galileo) allow manual selection of the termination flow percentage (flow criterion). This is designed to help clinicians fine-tune the ventilator inspiratory termination for individual patients. However, the setting of the termination flow percentage is difficult with visual observation of the airway pressure waveform at bedside and may be impossible when waveform analysis is unavailable.[8] Moreover, the patient effort and mechanics may change over time, which necessitates frequent adjustments by clinicians. Automatic variable termination criterion combined with appropriate pressure criterion seems more user friendly and may sufficiently improve the patient-ventilator synchrony.

Table Plateau Airway Pressure (in cm H_2O) for Three Pressi Support Ventilators Set at Positive End-Expiratory Pr of 0 or 5 cm H_2O (PEEP-0 or PEEP-5) and Tested at Compliance of 20, 40, or 80 (C20, C40, C80) and Parabolic Resistance of 5 or 20 (R5, R20).

		Demand L/m	
	NPB7200		
R5, C80		12.	10.8
R5, C40	8.5	11.	10.2
R5, C20	8.5	11.	10.2
R20, C8(			10.5
R20, C4(			10.7
R20, C2(			10.8
EEP-5			
R5, C80			10.
R5, C40	9.0		10.
R5, C20	8.6		10.
R20, C80	8.4		10.
R20, C40	8.5		
R20, C20	8.4	10.	

Lung model simulated spontan pressures are those above PEE (NPB7200), Siemens 300 (SV ts with low-demand peak llcor Puritan Bennett 7200 able 4. Peak Inspiratory Airway Pressure (in cm H_2O) for Three Pressure Support Ventilators Set at Positive End-Expiratory Pressure of 0 or 5 cm H_2O (PEEP-0 or PEEP-5) and Tested at Compliance of 20, 40, or 80 (C20, C40, C80) and Parabolic Resistance of 5 or 20 (R5, R20

	High Demand (60 L/mi			Low Demand (30 L/min		
	NPB7200	SV300	E200	NPB7200	SV300	E2
PEEP-0						
R5, C80		13	11	11		
R5, C40	12	14		11		12
R5, C20	13	14	12	11		13
R20, C80		16	13	11		
R20, C40	14	19	17	12	14	
R20, C20	14		16	11	18	
PEEP-5						
R5, C80	10		12	12	13	
R5, C40	12	15	12	12	13	13
R5, C20	13			12	14	13
R20, C80	12			12	13	13
R20, C40	13	20			14	12
R20, C20	14	22			18	13

mpartment lung model was used to simulate spontaneous breathing of patients with high- or low-demand peak flow. All pressures ar ve PEEP level. Ventilators: Nellcor Puritan Bennett 7200ae (NPB7200), Siemens 300 (SV300), Newport Wave E200 (E200).

ıble Inspiratory Area Percent (Area-I%) of Airway Pressure for Three Pressure Support Ventilator Set at Positive End-Expiratory Pressure of 0 or 5 cm H_2O (PEEP-0 or PEEP-5) and Tested at Compliance of 20, 40, or 80 (C20, C40, C80) and Parabolic Resistance of 5 or 20 (R5, R20).

	High Demand (60 L/min)			Low Demand (30 L/min)		
	NPB7200	SV300	E200	NPB7200	SV300	E200
PEEP-0						
R5, C80	33		55	55		69
R5, C40	39	56	60	60	67	70
R5, C20	43	56	61	57	66	67
R20, C80	39	65	26	62	73	72
R20, C40	35	69	70	59	73	72
R20, C20	46	66	69			
PEEP-5						
R5, C80	43		61	63	65	65
R5, C40	48	56	62	59	65	62
R5, C20	47	54	65	65	71	67
R20, C80	38	59	36	64		66
R20, C40	42	61	70	62		66
R20, C20	52	66	70	64		64

A two-compartment lung model was used to simulate spontaneous breathing of patients with high- or low-demand Nellcor Puritan Bennett 7200ae (NPB7200), Siemens 300 (SV300), Newport Wave E200 (E200).

The Wmus is a function of the trigger delay, actual pressure support level, and termination synchrony (premature termination or delayed termination). In this study, the calculation of the Wmus used only the pressure and volume of the driving phase; therefore, the delayed termination will not affect the appropriateness of the calculation of the Wmus. While there was not marked premature termination (Table 1) and the Wmus corresponding to the trigger phase only accounts for a minimal part of the total Wmus (data not shown), the difference in the Wmus mainly represents the difference of the inspiratory output of the ventilators.

Our results showed that the Wmus (J/L) was the highest in the NPB7200ae among all tested ventilators. This is the result of the insufficient initial flow delivery from the NPB7200ae. The insufficient initial flow delivery also

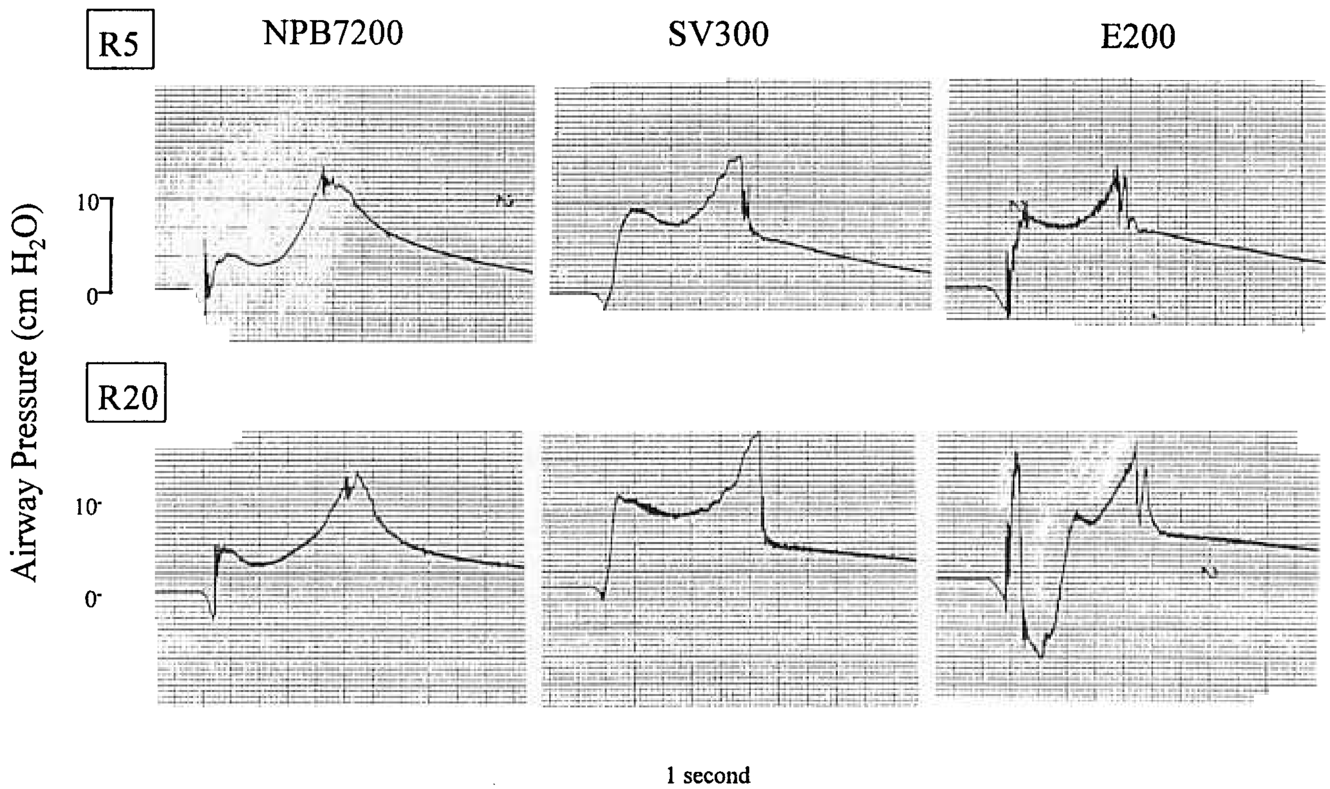

Fig. 4. The pressure waveforms in high demand. Patient demand: 60 L/min; Compliance: 80 mL/cmH2O; resistance: R5 (upper) and R20 (lower). NPB7200 = Nellcor Puritan Bennett 7200ae; SV300 = Servo 300; E200 = Wave E200.

causes pressure undershoot during the first half of the inspiratory phase.[6,18] This is consistent with the finding that the Area-I% in the NPB7200ae was also markedly lower than that in the other two ventilators. On the other hand, the Wmus in the SV300 was always the least among all tested ventilators due to the higher actual support pressure level. Although the pressure support level in the three ventilators was set at 10 cm H_2O, the actual plateau pressure was 1–2 cm H_2O higher than the set pressure support level in the SV300, suggesting excessive support. We set inspiratory rise time to 1% in the SV300 in order to shorten the negative airway pressure period because in our preliminary experiments we found a longer negative airway pressure period at a higher inspiratory rise time. Meanwhile, this fast pressurization did not cause pressure overshoot even in high resistance/low compliance conditions. The significant high peak inspiratory airway pressure in the SV300 appeared around the end, not the start, of inspiration. The high peak inspiratory airway pressure resulted from high pressure criterion (+20 cm H_2O above the target pressure) and low flow criterion (5% of peak flow). The trigger dyssynchrony in the E200 in high demand with long time constant conditions resulted from the initial pressure overshoot, suggesting the insufficient initial flow control algorithm under this condition.

Since our data are based on a lung model, careful consideration should be taken when extrapolating it to the clinical setting. In addition, there are several limitations in the design of our study. First, the 'patient' cannot actively exhale in our lung model. In clinical sites, active exhalation from the patient expiratory muscle activity may cause inspiratory flow decline quicker than it did in this study. This may shorten the ventilator inspiratory termination delay time; however, it would be at the cost of the patient expiratory muscle work.[16] Second, the pressure and flow signals used for analyses in this study were measured at the place between the tested ventilator and the tested lung. The flow and pressure signals used for the control of the flow delivery in the 3 ventilators are actually measured within ventilators, except that in the E200, the pressure is measured at the patient circuit proximal wye connector. This difference in the measurement locations may introduce some degree of error due to the breathing circuit. Last, we only simulated the patient T_I of 1.0 second. Shorter or longer patient T_I may change the termination delay time quantitatively. These limitations should be taken into account when interpreting the results of this study for clinical purposes. It should also be noted that the patient-ventilator synchrony in the transition to exhalation may not be solely the result of termination criteria. The timing of flow termination in a ventilator is also related to that ventilator's inspiratory output. Therefore, the results in this study may not be directly extrapolated to other ventilators using the same termination criteria.

Conclusion

In conclusion, the termination criteria used in PSV in the 3 ventilators provided a relatively reasonable patient-ventilator synchrony in the transition to exhalation in most settings. The marked delay in the ventilator inspiratory termination may occur under the conditions of long time constant with low demand in the SV300, which resulted mainly from the combination of the inappropriate pressure criteria and flow criteria. Although the pressure criteria are designed as a backup measure to the flow criteria in the inspiratory termination, it consistently functions as a primary mechanism in the NPB7200ae.

PRODUCT SOURCES

Ventilators

Nellcor Puritan Bennett 7200ae, Mallinckrodt Inc, Pleasanton CA

Servo 300, Siemens Medical Systems Inc, Iselin NJ

Wave E200, Newport Medical Instruments Inc, Costa Mesa CA

BEAR-5, Thermo Respiratory Group, Palm Springs, CA

Flow Transducer

Model RF-L, Minato Medical Science Co. Ltd., Osaka, Japan

Pressure Transducer

Heise 901A, Dresser Industries Inc, Stratford CT

Data Acquisition System

DT2831 and Global Lab, Data Translation Inc, Marlborough MA

Lung Model

TTL Model 1600, Michigan Instruments Inc, Grand Rapids MI

Calibration Analyzer

RT-200, Allied Healthcare Products, St Louis MO

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