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Effects of different triggering systems and external PEEP on trigger capability of the ventilator

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Abstract *Objective:* The triggering capability of both the pressure and flow triggering systems of the Servo 300 ventilator (Siemens-Elema, Sweden) was compared at various levels of positive end-expiratory pressure (PEEP), airway resistance (R_{aw}), inspiratory effort and air leak, using a mechanical lung model.
Design: The ventilator was connected to a two bellows-in-series-type lung model with various mechanical properties. Lung complicance and chest wall compliance were 0.03 and 0.12 l/cmH_2O, respectively. R_{aw} was 5, 20 and 50 $cmH_2O/l/s$. Respiratory rate was 15 breaths/min. To compare the triggering capability of both systems, the sensitivity of pressure and flow triggered pressure support ventilation (PSV) was adjusted to be equal by observing the triggering time at 0 cmH_2O PEEP and 16 cmH_2O of pressure support (PS) with no air leak. No auto-PEEP was developed. In the measurement of trigger delay, the PS level ranged from 16 to 22 cmH_2O to attain a set tidal volume (V_T) of 470 ml at a R_{aw} of 5, 20 and 50 $cmH_2O/l/s$. The PEEP level was then changed from 0, 5 and 10 cmH_2O at a PS level of 17 cmH_2O and R_{aw} of 5 and 20 $cmH_2O/l/s$, and the trigger delay was determined. The effect of various levels of air leak and inspiratory effort on triggering capability was also evaluated. Inspiratory effort during triggering delay was estimated by measurements of pressure differentials of airway pressure (P_{aw}) and driving pressure in the diaphragm bellows (P_{driv}) in both systems.
Measurements and results: There were no significant differences in trigger delay between the two triggering systems at the various PEEP and R_{aw} levels. At the matched sensitivity level, air leak decreased trigger delay in both systems, and additional PEEP caused auto-cycling. A low inspiratory drive increased trigger delay in the pressure sensing system, while trigger delay was not affected in the flow sensing system. The P_{aw} and P_{driv} differentials were lower in flow triggering than in pressure triggering.
Conclusions: With respect to triggering delay, the triggering capabilities of the pressure and flow sensing systems were comparable with and without PEEP and/or high airway resistance at the same sensitivity level, unless low inspiratory drive and air leak were present. In terms of pressure differentials, the flow triggering system may require less inspiratory effort to trigger the ventilator than that of the pressure triggering system with a comparable triggering time. However, this difference may be extremely small.

Key words Work of breathing · Pressure support ventilation · Lung model · Artificial ventilation · Ventilators · Trigger delay

Introduction

Both flow and pressure triggering systems are incorporated in most modern ventilators run by microprocessors [1, 2]. The triggering capability of these sensing systems and their responsiveness to patient effort were evaluated in terms of trigger delay [3, 4]. The factors that affected trigger delay were the trigger method and sensitivity, the magnitude of patient inspiratory effort, auto-PEEP (positive end-expiratory pressure), and externally applied PEEP [5]. According to Sassoon and other investigators [5–9], the flow-triggering system is more sensitive than the pressure-triggering system. However, although the highest sensitivity that did no cause auto-cycling was taken in both systems, the direct comparison of the triggering capability of both sensing mechanisms had a significant problem; the set sensitivity of both systems may be different, which would lead to a significant error in comparison.

The purpose of this study was to compare the triggering capability of both pressure and flow triggering during pressure support ventilation (PSV) on the basis that equal sensitivity in terms of trigger time was preset for both systems. Under these conditions, the triggering capability of both systems was examined at different levels of external PEEP, airway resistance, inspiratory drive and air leak. Our lung model was designed to simulate spontaneous breathing with various mechanical properties. It allowed us to measure accurately trigger delay, which was defined as the interval from the onset of spontaneous ventilatory activity to the initiation of fresh gas delivery into the lung.

Materials and methods

A mechanical lung model was used in our study. Details on the model have already been described by Takahashi et al. [10]. The model consisted of two bellows in series suspended by springs (Fig. 1). As an analog of the lung, one bellows was attached in sequence to the ventilator. Analogous to the diaphragm, the remaining bellows was attached to a jet flow generator providing the spontaneous inspiratory effort. Both bellows were surrounded by air space regarded as the pleural space in which the pressure was subatmospheric. Lung compliance (L) was set as 0.03 l/cmH_2O, and chest wall compliance was 0.12 l/cmH_2O. Airway resistance (R_{aw}) of either 5, 20 or 50 cmH_2O/l/s was added by placing resistors of various diameters between the lung and ventilator. A Venturi mechanism of jet flow was used to provide negative pressure inside the diaphragm bellows. The jet flow generator can be driven at a set respiratory rate (RR), driving pressure and inspiratory : expiratory ratio. A waveform of negative pressure in the diaphragm bellows (P_{driv}), thought to be equivalent to respiratory muscle pressure (P_{mus}), was applied inside the diaphragm bellows. The waveform of P_{driv} was adjusted to become exponential by interposing capacitance and resistance between the jet flow generator and diaphragm bellows. The magnitude of P_{driv} was adjusted by regulating the driving pressure of the jet flow generator. The pressure profile, peak flow rate (0.23 l/s) and magnitude of P_{driv} were maintained in each setting. Inspiratory effort was transmitted through the pleural space to the lung bellows, allowing the lung bellows to expand, which resulted in gas entering the lung. During exhalation, jet flow was interrupted and the diaphragm bellows was opened to the atmosphere. At the end of expiration, the diaphragm bellows returned passively to the initial level, which was equal to a functional residual capacity of approximately 2000 ml in our model.

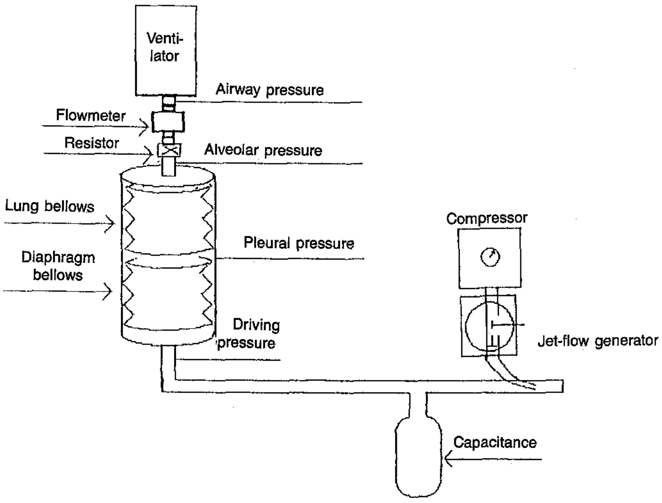

Fig. 1 Schematic representation of the lung model

Flow was measured with a hot-wire flow manometer (Minato ATD 105, Osaka, Japan) calibrated with a 2 l syringe. The flow signal was used for volume measurements. Pleural pressure (P_{pl}), P_{driv}, pre- and postresistor pressure, which were considered as airway opening pressure (P_{aw}) and alveolar pressure (P_{alv}), respectively, were measured with separate pressure transducers. Auto-PEEP was determined as end-expiratory P_{alv} exceeding the externally applied PEEP. All variables were monitored and recorded on a multichannel strip-chart recorder (Omnicorder, Sanei, Tokyo, Japan). Trigger delay was determined as an interval from the onset of inspiratory effort indicated by onset of negative deflection on the P_{driv} curve to the onset of flow delivery into the lung (Fig. 2). High-speed tracings were used to analyze trigger delay. The Servo 300 ventilator (Siemens-Elema, Sweden) was examined with both pressure and flow sensing mechanisms. A standard ventilator circuit without a humidifier was used in all the experiments.

Protocol

PSV was delivered by the Servo 300 ventilator connected to the lung model. The triggering capability of the ventilator was evaluated in the absence of auto-PEEP. To avoid the development of auto-PEEP, a low RR of 15 breaths/min and an inspiratory : expiratory ratio of 1 : 3 were used in all the experimental settings. At each setting, P_{driv} was adjusted to obtain a tidal volume (V_T) of 190 ml during T-piece breathing at a R_{aw} of 5 cmH_2O. The magnitude of P_{driv} was not changed during any settings except one with varied inspiratory effort. At a PEEP level of 0 cmH_2O, R_{aw} of 5 cmH_2O and a pressure support (PS) level of 16 cmH_2O, the triggering sensitivity of both pressure and flow were adjusted to be equal. To accomplish this, sensitivity of flow-triggered PSV was adjusted to obtain the trigger delay equal to that in pressure-triggered PSV at a sensitivity of −0.3 cmH_2O. At this fixed sensitivity level, trigger delay was compared between flow and pressure triggered PSV under the following experimental conditions. First, the PS level was arbi-

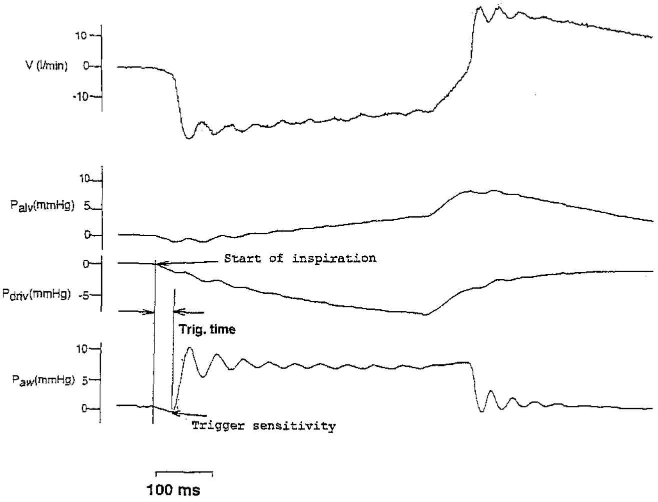

Fig. 2 Determination of trigger delay. Pressure triggered pressure support ventilation (*PSV*) is provided by the Servo 300 ventilator at a pressure support level of 10 $\mathrm{cmH_2O}$ without positive end-expiratory pressure (*PEEP*). Lung compliance = 0.03 $\mathrm{l/cmH_2O}$; airway resistance = 50 $\mathrm{cmH_2O/l/s}$; respiratory rate = 15 breath/min. Pressure-time and flow-time tracings are obtained during PSV without PEEP. The ventilator is triggered when airway pressure (or base flow rate) drops to preset triggering level. Onset of inspiratory effort is indicated by negative deflection on P_{driv} time curve. (P_{alv} alveolar pressure, P_{driv} driving pressure in the diaphragm bellows, P_{aw} airway pressure)

trarily increased from 16 to 22 $\mathrm{cmH_2O}$ to deliver a set V_T of 470 ml at the various R_{aw} settings. Second, with a $R_{aw}$of 5 and 20 $\mathrm{cmH_2O}$ and PS level of 17 $\mathrm{cmH_2O}$, 5 and 10 $\mathrm{cmH_2O}$ PEEP were added. Third, two levels of air leak were created at an RR of 15 breaths/min, PS level of 17 $\mathrm{cmH_2O}$ and PEEP of 0 and 5 $\mathrm{cmH_2O}$. Fourth, the magnitude of P_{driv} was reduced, resulting in a decrease in V_T from 190–110 ml during T-piece breathing (peak inspiratory flow rate was 0.16 l/s). The PS level was 17 $\mathrm{cmH_2O}$ with external PEEP 0, 5 and 10 $\mathrm{cmH_2O}$, RR 15 breaths/min and R_{aw} 50 $\mathrm{cmH_2O/l/s}$. Pressure differentials were calculated in both triggering systems using P_{aw} and P_{driv} curves. Pressure differentials for each triggering period were taken for analysis. In each setting, analysis of trigger delay variance was performed over five breathing cycles using Student *t*-test, and the mean ± standard error was calculated.

Results

The scope of triggering capability was expressed as trigger delay and pressure differentials (P_{aw}/dt and P_{driv}/dt) obtained in both systems. The results are shown in Tables 1–4. Figure 2 illustrates the method of measuring the trigger delay obtained from P_{driv} and P_{aw} curves. There were no differences in trigger delay between flow or pressure triggered PSV with varied R_{aw}, at the set V_T of 470 ml, which was accomplished by increasing the PS levels at various levels of PEEP and R_{aw} (Table 1). As Table 2 shows, trigger delay was significantly increased during pressure triggered PSV by 5 $\mathrm{cmH_2O}$ PEEP, while no significant increase was observed in the flow triggered system at 5 $\mathrm{cmH_2O}$ PEEP. This phenomenon was similarly observed at a R_{aw} of 5 and and 20 $\mathrm{cmH_2O/l/s}$. However, at 10 $\mathrm{cmH_2O}$ PEEP, trigger delay was significantly increased in both systems.

Table 1 Triggering delay in pressure and flow triggering systems at different levels of airway resistance and pressure support (mean ± SEM). Triggering delay in both systems was compared with control data at R_{aw} 5 $\mathrm{cmH_2O/l/s}$ and PS level 16 $\mathrm{cmH_2O}$ (*P-trig* pressure triggering, *F-trig* flow triggering, *Trig delay* trigger delay, *dP_{aw}/dt* airway pressure differentials, *dP_{driv}/dt* driving pressure differentials). C_L: 0.03 $\mathrm{l/cmH_2O}$; RR: 15 breaths/min, V_T: 470 ml

R_{aw} ($\mathrm{cmH_2O/l/s}$)	5	20	50
PS level ($\mathrm{cmH_2O}$)	16	18	22
Trig delay			
P-trig (ms)	60.5 ± 1.3	62.0 ± 2.1	61.5 ± 2.1
dP_{aw}/dt ($\mathrm{cmH_2O/ms}$)	0.03 ± 0.001	0.02 ± 0.001	0.02 ± 0.001
dP_{driv}/dt ($\mathrm{cmH_2O/ms}$)	0.05 ± 0.001	0.06 ± 0.003	0.05 ± 0.001
F-trig (ms)	59.0 ± 0.8	60.5 ± 1.9	62.2 ± 2.5
dP_{aw}/dt ($\mathrm{cmH_2O/ms}$)	0.02 ± 0.001	0.01 ± 0.004	0.01 ± 0.001
dP_{driv}/dt ($\mathrm{cmH_2O/ms}$)	0.06 ± 0.001	0.06 ± 0.001	0.05 ± 0.004

Table 2 Effect of PEEP on trigger delay in pressure and flow triggering systems at different airway resistance (mean ± SEM). *P-trig* pressure triggering, *F-trig* flow triggering, *dP_{aw}/dt* airway pressure differentials, *dP_{driv}/dt* driving pressure differentials. C_L: 0.03 $\mathrm{l/cmH_2O}$; RR: 15 breaths/min; PS level: 17 $\mathrm{cmH_2O}$ (at R_{aw} = 5) and 19 $\mathrm{cmH_2O}$ (at R_{aw} = 20); V_T: 480 ml

	PEEP level ($\mathrm{cmH_2O}$)		
Trig delay	0	5	10
R_{aw} = 5 $\mathrm{cmH_2O/l/s}$			
P-trig (ms)	61.40 ± 2.2	77.8 ± 4.3*	89.8 ± 2.0*
dP_{aw}/dt ($\mathrm{cmH_2O/ms}$)	0.02 ± 0.001	0.03 ± 0.003	0.03 ± 0.002
dP_{driv}/dt ($\mathrm{cmH_2O/ms}$)	0.05 ± 0.001	0.06 ± 0.002	0.06 ± 0.003
F-trig (ms)	61.2 ± 1.7	68.0 ± 2.9	75.4 ± 2.1*,**
dP_{aw}/dt ($\mathrm{cmH_2O/ms}$)	0.01 ± 0.001	0.02 ± 0.001	0.02 ± 0.001
dP_{driv}/dt ($\mathrm{cmH_2O/ms}$)	0.04 ± 0.001	0.05 ± 0.001	0.05 ± 0.003
R_{aw} = 20 $\mathrm{cmH_2O/l/s}$			
P-trig (ms)	60.8 ± 2.0	78.6 ± 3.6*	85.0 ± 3.3*
dP_{aw}/dt ($\mathrm{cmH_2O/ms}$)	0.035 ± 0.001	0.03 ± 0.004	0.04 ± 0.005
dP_{driv}/dt ($\mathrm{cmH_2O/ms}$)	0.06 ± 0.001	0.06 ± 0.003	0.07 ± 0.004
F-trig (ms)	62.0 ± 1.5	68.6 ± 4.9	71.6 ± 3.2*,**
dP_{aw}/dt ($\mathrm{cmH_2O/ms}$)	0.02 ± 0.001	0.02 ± 0.001	0.03 ± 0.001
dP_{driv}/dt ($\mathrm{cmH_2O/ms}$)	0.05 ± 0.001	0.05 ± 0.003	0.06 ± 0.004

*$p < 0.01$ vs PEEP = 0; **$p < 0.01$ vs P-trig

Table 3 Trigger delay in pressure and flow triggering systems at different levels of inspiratory effort and PEEP level (mean ± SEM). *P-trig* pressure triggering, *F-trig* flow triggering, P_{driv1}, P_{driv2}: driving pressure in the diaphragm bellows, $P_{driv1} > P_{driv2}$; dP_{aw}/dt airway pressure differentials, dP_{driv}/dt driving pressure differentials. C_L: 0.03 l/cmH_2O; R_{aw}: 50 cmH_2O/l/s; RR: 15 breaths/min; PS level: 17 cmH_2O; V_T: 340 ml

Trig delay	P_{driv1} PEEP 0	P_{driv2} PEEP 0	P_{driv2} PEEP 5	P_{driv2} PEEP 10
P-trig (ms)	62.0 ± 2.4	90.7 ± 7.8*	95.5 ± 3.1*	103.0 ± 6.2*
dP_{aw}/dt (cmH_2O/ms)	0.02 ± 0.002	0.03 ± 0.001	0.03 ± 0.001	0.03 ± 0.002
dP_{driv}/dt (cmH_2O/ms)	0.05 ± 0.004	0.04 ± 0.003	0.03 ± 0.003	0.02 ± 0.001
F-trig (ms)	60.4 ± 1.6	69.2 ± 5.1	78.4 ± 3.2*,**	79.5 ± 3.1*,**
dP_{aw}/dt (cmH_2O/ms)	0.01 ± 0.001	0.02 ± 0.002	0.03 ± 0.003	0.03 ± 0.001
dP_{driv}/dt (cmH_2O/ms)	0.05 ± 0.001	0.03 ± 0.001	0.03 ± 0.001	0.03 ± 0.002

*$p < 0.01$ vs P_{driv1}, PEEP = 0; **$p < 0.01$ vs P-trig

As Table 3 shows, both sensing systems were examined by changing the magnitude of inspiratory drive and PEEP level at the matched V_T and R_{aw} of 50 cmH_2O. During pressure sensing, trigger delay was increased by reducing P_{driv} (P_{driv}2) in comparison with that in the control P_{driv} (P_{driv}1) without PEEP. However, it did not affect trigger delay in flow-triggered PSV at 0 cmH_2O PEEP. Trigger delay was increased in both modes, when PEEP was further increased to 5 and 10 cmH_2O at the reduced P_{driv}.

Table 4 shows the effect of air leak on triggering capability in pressure- or flow-triggered PSV. A small air leak (10% leakage) decreased trigger delay in both systems, but the difference was non-significant. External PEEP resulted in auto-cycling (Table 4). In the presence of a large air leak (30% leakage), as indicated by considerable differences in inspiratory:expiratory V_T, trigger delay was significantly decreased in both systems. Adding 5 cmH_2O PEEP also caused autocycling.

During all the experiments the settings for P_{aw} and P_{driv} differentials were lower in the flow-triggering system than in the pressure-triggering system. However, the difference was not significant except for the experiment with varied PEEP (Table 2).

Table 4 Effect of air leak on triggering capabilities of pressure and flow triggering systems with and without PEEP at the matched sensitivity level. *P-trig* pressure triggering, *F-trig* flow triggering, dP_{aw}/dt airway pressure differentials, dP_{driv}/dt driving pressure differentials, C_L: 0.03 l/cmH_2O; R_{aw}: 5 cmH_2O/l/s; RR: 15 breaths/min; PS level: 17 cmH_2O; PEEP level: 5 cmH_2O

Trig delay	Air leak (−)	air leak (+)	PEEP (+), air leak (+)
(a) Small air leak inspiratory/expiratory V_T = 480/390 ml (P-trig); 500/390 ml (F-trig)]			
P-trig (ms)	61.4 ± 2.2	57.7 ± 2.2	auto-cycling
dP_{aw}/dt (cmH_2O/ms)	0.03 ± 0.001	0.02 ± 0.003	
dP_{driv}/dt (cmH_2O/ms)	0.05 ± 0.001	0.04 ± 0.003	
F-trig (ms)	60.4 ± 1.6	52.0 ± 2.2	auto-cycling
dP_{aw}/dt (cmH_2O/ms)	0.02 ± 0.002	0.02 ± 0.001	
dP_{driv}/dt (cmH_2O/ms)	0.04 ± 0.003	0.03 ± 0.003	
(b) Large air leak [inspiratory/expiratory V_T = 805/314 ml (P-trig); 811/314 ml (F-trig)]			
P-trig (ms)	56.0 ± 2.4	32.5 ± 6.1*	auto-cycling
dP_{aw}/dt (cmH_2O/ms)	0.03 ± 0.003	0.02 ± 0.002	
dP_{driv}/dt (cmH_2O/ms)	0.05 ± 0.003	0.05 ± 0.004	
F-trig (ms)	56.6 ± 2.2	39.3 ± 1.2*	auto-cycling
dP_{aw}/dt (cmH_2O/ms)	0.02 ± 0.001	0.01 ± 0.003	
dP_{driv}/dt (cmH_2O/ms)	0.04 ± 0.001	0.03 ± 0.003	

*$p < 0.01$ vs no air leak

Discussion

In our study, a comparison of the triggering capability of pressure- and flow-triggering systems was made on the basis that identical sensitivity in terms of trigger time was preset in both triggering systems. This was confirmed since an identical trigger delay was obtained by adjusting the sensitivity of both triggering systems at 0 cmH_2O PEEP and no auto-PEEP without air leak. For two triggering methods to be equal, the component of triggering capability expressed as pressure differential should be equal. In our experiment, P_{driv} was considered as patient inspiratory effort of P_{mus}. Pressure differentials (dP_{driv}/dt) tended to be smaller in the flow-sensing system; however, the difference was non-significant in both systems except during increasing PEEP. We consider the direct measurement of triggering capability of both systems more informative than the observation of the characteristics of pressure time product. Sassoon et al. compared pressure and flow-triggering systems [5, 6] and confirmed the superiority of flow triggering. Their methods and ours are essentially the same; however, it is likely that the sensitivity of both sensing systems was different in their study. Direct measurement of inspiratory effort (P_{driv}) and/or triggering time interval, as we carried out, may allow us to evaluate sensitivity level more accurately. In our lung model study, the lowest adult sensitivity level of the flow-sensing system corresponded to a sensitivity of 0.3 cmH_2O in the pressure-sensing system, when no PEEP and air leak were present. The advantage of this method under equivalent trial conditions was the ability to make a more objective interpretation of trigger characteristic evaluations. The influence of auto-PEEP on the ventilator's triggering capability was avoided by using the low respiratory rate and low I:E ratio.

The magnitude of inspiratory effort, externally applied PEEP and air-leak all affected triggering time, but an increase in airway resistance did not influence the triggering capability of either system. It is suggested that high airway resistance can prolong triggering time only with the development of auto-PEEP.

Regardless of R_{aw}, the effect of PEEP on the sensing mechanisms resulted in a trivial increase in triggering time delay. This increase was smaller in flow-triggered PSV than in pressure-triggered PSV. However, this difference has little clinical relevance.

In general, the difference in trigger delay between the two sensing systems can be caused by the presence of base flow and a different sensing mechanism; the presence of base flow is an added threshold for pressure triggering, while it does not affect the threshold for flow sensing. The changes in trigger delay by PEEP within the same sensing system can be interpreted as a difference in regulation of both the exhalation valve and PEEP device [11–13]. Expiratory resistance in the ventilator breathing circuit can be affected by the intrinsic resistance of the exhalation valve or the inefficiency of the ventilator in totally releasing pressure from the cap of the valve or exhalation valve gate [14, 15]. Inadequate operation of a PEEP-producing expiratory valve and expiratory limb resistance have been reported to affect the ventilator's triggering capability [16, 17]. However, none of these factors was likely to occur in our study because the end-expiratory airway pressure returned to the set PEEP level in both systems. Thus, the precise mechanism causing this small difference in trigger delay within the systems is unknown.

In our lung model, inspiratory effort was generated by negative driving pressure applied to the diaphragm bellows. Similar to P_{mus}, which represented patient inspiratory effort [18], P_{driv} waveform was changed to simulate weak inspiratory effort. A decrease in P_{driv} resulted in greater trigger delay in the pressure-sensing mechanism, while it did not affect triggering time in flow-triggered PSV. This is because the airway pressure differential is important in triggering the ventilator in pressure-sensing PSV. However, the difference in trigger delay between the two sensing systems was small.

In the Servo 300 base flow circulates inside the respiratory circuit during the entire respiratory phase whether or not air leak is present. If the leak flow rate was less than the base flow rate, trigger delay was decreased in both systems, because the actual sensing threshold for flow and pressure was decreased. When the leak flow exceeded the base flow rate, auto-cycling occurred in both systems because leakage exceeding the set triggering flow rate or set pressure sensitivity is recognized as inspiratory effort.

In summary, the evaluation of trigger delay in both pressure- and flow-triggering systems with and without PEEP with similar sensitivity demonstrated comparable triggering capabilities, unless weak inspiratory drive and/or air leak was present. Flow triggering had an advantage over pressure triggering from the perspective of the level of inspiratory effort necessary to trigger the ventilator. However, this difference has little clinical relevance.

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