Using Tracheal Pressure to Trigger the Ventilator and Control Airway Pressure During Continuous Positive Airway Pressure Decreases Work of Breathing*

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Study objective: We evaluated the difference in work of breathing (WOB) during spontaneous ventilation with continuous positive airway pressure (CPAP) among three methods of triggering the ventilator: conventional pressure triggering, tracheal pressure triggering, and flow-by triggering.

Methods: In an in vitro model of the respiratory system consisting of a bellows (lungs) in a plastic canister (chest wall), spontaneous ventilation was simulated with a piston-driven pump (respiratory muscles). Data were recorded during CPAP of 5 cm H2O (model 7200ae ventilator, Puritan-Bennett, Overland Park, Kan) at peak sinusoidal inspiratory flow rate demands of 60 and 50 L/min and airway resistances of 5 and 20 cm H2O/L/s, with the demand flow system triggered by conventional pressure, tracheal pressure, or flow. Under each condition, tidal volume, pressure-time product (PTP), WOB, and changes in intrapleural pressure (Ppl) and airway pressure were recorded in real time by means of a computerized portable respiratory monitor (model CP-100, Bicore, Irvine, Calif). The Ppl was measured from within the canister, tidal volume by positioning a flow sensor between the Y-piece of the breathing circuit and the endotracheal tube (ETT), and airway pressure from a catheter attached to the flow sensor. The WOB was calculated by the monitor in real time.

In recent years, researchers have attempted to synchronize ventilatory support with physiologic spontaneous inspiratory effort. For example, pressure support ventilation (PSV) should begin simultaneously with the onset of inspiratory effort, provide flow synchronously with peak inspiratory flow rate demand, and provide enough airway pressure to partially or totally unload respiratory muscles. A better patient-ventilator interaction should lessen work of breathing (WOB), improve comfort, and, thus, possibly lessen the need for sedation.

The signal that triggers the demand-flow system of a ventilator is designed to respond to inspiratory effort. With PSV, most ventilators sense a set decrease in airway pressure (generally measured at the Y-piece of the breathing circuit at the onset of spontaneous inhalation) with an internal pressure-triggering transducer that detects inspiratory effort. The endotracheal tube (ETT), breathing circuit tubing, and valves in the ventilator are interposed between the transducer and the source of inspiratory effort—the respiratory muscles. Therefore, under some circumstances, ventilators

Results: Changes in Ppl were greatest with conventional pressure triggering, less with flow-by triggering, and least with tracheal pressure triggering. The WOB was significantly lower (approximately 50%) with tracheal pressure triggering than with the other two methods. With tracheal pressure triggering only, an effect similar to that of pressure support ventilation (PSV) occurred, which accounted in part for the significant decrease in WOB. The PTP/breath ratio correlated strongly and was a good predictor of WOB (r²=0.95).

Conclusions: Compared with conventional pressure and flow-by methods, triggering with tracheal pressure decrease WOB significantly. This method of triggering may improve patient-ventilator interaction. (CHEST 1995; 108:509-14)

Key words: demand-flow triggering; mechanical ventilation; pressure support ventilation; respiratory monitoring; respiratory muscles; pressure-time product; work of breathing

CPAP=continuous positive airway pressure; ETT=endotracheal tube; Ppl=intrapleural pressure; PSV=pressure support ventilation; PTP=pressure-time product; WOB=work of breathing

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can be insensitive and unresponsive to respiratory effort. For example, a large change in intrapleural pressure (Ppl) may be required before air flows into the lungs, which can impose an isometric load on the respiratory muscles at the beginning of inhalation and result in patient-ventilator dyssynchrony and, thus, muscle loading and fatigue.\(^5\)

The ventilator we used (model 7200ae, Puritan-Bennett, Overland Park, Kan) offers the option of using flow rather than pressure to trigger breaths. A continuous flow rate, for example, 6 L/min, is directed through the breathing circuit, and sensitivity to flow is set, for example, at 3 L/min. The demand-flow system is triggered when, at the onset of inhalation, at least 3 L/min of gas is diverted from the breathing circuit into the ETT. The system is flow-cycled off when the total exhaled flow rate exceeds the set continuous flow rate by 2 L/min, in this case, 8 L/min.\(^4\) Flow-by-triggering may engender less WOB than conventional pressure triggering.\(^5\)

In theory, moving the triggering site closer to the respiratory muscles should reduce the change in Ppl needed to trigger the ventilator.\(^2\) Indeed, using tracheal pressure to trigger the demand-flow continuous positive airway pressure (CPAP) system by triggering the ventilator at the tracheal or carinal end of the ETT significantly decreased imposed WOB compared with conventional pressure or flow-by-triggering.\(^6\) However, the total WOB (physiologic plus imposed) was not measured, so no inference can be made about the effect of tracheal pressure triggering on the risk of respiratory muscle fatigue. We undertook the present study to compare total WOB during spontaneous ventilation with CPAP among the three methods of triggering the ventilator.

**METHODS**

Spontaneous breathing was simulated with an *in vitro* model of the respiratory system (Fig 1). The model consisted of a bellows (lung) in a plastic canister (chest wall). Total respiratory system compliance was approximately 60 mL/cm H\(_2\)O. A normal chest wall compliance of 200 mL/cm H\(_2\)O was used for calculations of WOB. Airway resistance was adjusted to 5 or 20 cm H\(_2\)O/L/s by inserting parabolic resistors between the ETT and the bellows. A reciprocating piston-driven pump attached to a hole in the canister intermittently decreased pressure within the canister to simulate changes in Ppl. A tidal volume of 500 mL, a respiratory rate of 12 breaths/min, and an inhalation/exhalation time ratio of 0.5 were simulated. The model's trachea was intubated with an 8-mm internal diameter ETT. CPAP of approximately 5 cm H\(_2\)O was applied and pressure sensitivity for triggering was set at -2 cm H\(_2\)O. Conventional pressure, tracheal pressure, and flow-by-triggering were compared (Fig 1). Peak sinusoidal inspiratory flow rate demand was simulated at 60 and 80 L/min with different combinations of airway resistance and triggering method. Measurements were repeated five times with each test condition.

Work of breathing was measured automatically by a commercially available respiratory monitor (model CP-100, Bicore, Irvine, Calif) and by using Campbell's diagram (Fig 1). The Campbell diagram (Fig 1) can be used to determine the WOB from measurements of intrapleural pressure and flow. The following equation was used to determine the work of breathing:

\[
W = P \times V
\]

where \(W\) is work, \(P\) is intrapleural pressure, and \(V\) is volume of flow. The work of breathing was divided into two components: resistive (R) and elastic (E) work:

\[
\text{Work Of Breathing} = \text{Resistive Work} + \text{Elastic Work}
\]

**Figure 1.** Mechanical model used to measure work of breathing. Pressure changes at different sites, and volume and flow rate during simulated spontaneous breathing with continuous positive airway pressure and different methods of triggering the demand-flow system of a mechanical ventilator. As derived from the Campbell diagram by the respiratory monitor, the arrows in the pressure-volume loop of the diagram refer to inhalation (I) and exhalation (E). Simulated intrapleural pressure becomes negative during inhalation and returns to zero on exhalation. The negative sign within the canister refers to the negative pressure generated by the piston-driven pump. The site at which the demand-flow system of the ventilator was triggered was changed by changing the stopcock position from the exhalation limb of the breathing circuit to the catheter, which ended at the carinal end of the endotracheal tube. Work of breathing consisted of the sum of inspiratory resistive work (physiologic plus the work imposed by the breathing apparatus) and inspiratory elastic work. \(C_l\)=lung compliance; \(C_w\)=chest wall compliance; P-B=Puritan-Bennett.
nal pressure. Data variance and least WOB, the work required to overcome the elastic forces during inspiration; resistive WOB, the work required to overcome the resistance of the airways and pulmonary tissues to the flow of gas; and the imposed resistive WOB, the work required to breathe spontaneously through the breathing apparatus (the ETT, the ventilator breathing circuit tubing, and the demand-fl ow system). The monitor also measures changes in Pp and the pressure-time product (PTP) (the area in the curve subtended between the chest wall compliance line and the Pp-time curve). Data were analyzed with a three-factor analysis of variance and a Tukey multiple comparison test. Alpha was set at 0.05 for statistical significance.

RESULTS

Intrapleural pressure changed most with conventional pressure triggering, less with flow-by triggering, and least with tracheal pressure triggering (Fig 2). This pattern was consistent regardless of flow rate demand or airway resistance. The Pp change was more pronounced with higher airway resistance and flow rate demand. Statistically, WOB was significantly lower with tracheal pressure triggering than with conventional pressure or flow-by triggering under all conditions (Fig 3). Although statistically significant, the difference between flow and conventional pressure triggering was less pronounced (approximately 5 to 10%) than the difference between tracheal pressure triggering and the other two modes of triggering (approximately 45 to 55%). With higher peak inspiratory flow rate demand or increased airway resistance, the differences among the modes of triggering were more pronounced.

The WOB decreased more with tracheal pressure triggering than with conventional pressure or flow-by triggering because of a PSV-like effect (Fig 4). At peak inspiratory flow rate, a positive airway pressure of approximately 15 cm H₂O (measured at the Y-piece) was generated, with tracheal pressure triggering at a peak inspiratory flow demand of 60 L/min and an airway resistance of 20 cm H₂O/L/sec. The estimated WOB for conventional pressure triggering was approximately 30% lower than flow-by triggering.

Figure 2. Pleural pressure change (mean) at two different inspiratory (insp) flow rate demands and two different airway resistances with the demand-flow system of a ventilator triggered by conventional pressure (CP), tracheal pressure (TP), or flow-by (FB). With the higher flow rate demand and higher airway resistance, pleural pressure change differed most between TP triggering and both other methods. p<0.05 compared with CP (asterisk) and FB (dagger).

Figure 3. Work of breathing (WOB) (mean±SD) at two different inspiratory (insp) flow rate demands and two different airway resistances with the demand-flow system of a ventilator triggered by conventional (CP) or tracheal pressure (TP) or by flow (flow-by triggering [FB]). Under most conditions, WOB decreased by approximately 50% with TP triggering compared with CP or FB. p<0.05 compared with CP (asterisk) and FB (dagger).
resistance of 5 cm H₂O/L/s. This PSV-like effect varied with test conditions but occurred consistently only with tracheal pressure triggering. As a result, the change in Ppl needed to move the same gas volume at the same peak inspiratory flow rate demand was considerably less with tracheal pressure triggering than with the other modes (Fig 4).

The PTP/breath ratio correlated well and was an excellent predictor of WOB ($r^2=0.95$, $p<0.001$, $n=60$):

$$ WOB = -0.244 + 0.176 \times \text{PTP/breath}. $$

**DISCUSSION**

The main finding of the present study was that, under most conditions, tracheal pressure triggering decreased WOB by about 50% compared with triggering by conventional pressure or flow. Increasing airway resistance or inspiratory flow rate demand increased this difference. The need to overcome the breathing apparatus resistance to trigger the demand-flow system is negligible when it is triggered from the carinal end of the ETT. This is especially important when increased respiratory muscle loading is intolerable due to compromised pulmonary mechanics or when the trachea is intubated with a small internal diameter ETT, causing the increased imposed WOB to be possibly greater than physiologic WOB.⁹

These laboratory findings are consistent with a clinical study in which tracheal pressure triggering was found to decrease total WOB by about 35% compared with conventional pressure and flow-by triggering.¹⁰ During tracheal pressure triggering, a PSV-like effect decreased imposed WOB to almost zero, resulting in a decreased total WOB.

The difference in WOB between triggering by conventional pressure or by flow can be traced to the different algorithms by which the ventilator (Puritan-Bennett 7200ae) is pressure-targeted in each mode. With conventional pressure triggering and a CPAP of 5 cm H₂O, for example, the ventilator attempts to maintain the set level of CPAP minus the level of triggering sensitivity (-2 cm H₂O) set at the Y-piece of the breathing circuit. Thus, the ventilator attempts to maintain a pressure of 3 cm H₂O. With flow-by triggering, the ventilator attempts to maintain a pressure of CPAP plus 0.5 cm H₂O, or 5.5 cm H₂O. The greater the change in airway pressure, the greater the WOB. Hence, the different pressure-targets account for most of the difference in WOB between flow and conventional pressure triggering.¹¹ In the case of tracheal pressure triggering, the ventilator attempts to maintain an airway pressure of 3 cm H₂O at the carinal end of the ETT. Under these conditions, positive pressure is generated at the Y-piece, and is significantly greater than 3 cm H₂O because of the pressure drop (resistance) across the ETT.⁶ Pressure at the Y-piece was approximately 15 cm H₂O (Fig 4). As a result, a PSV-like effect occurred when the ventilator was triggered at the carinal end of the ETT, contributing to the significantly decreased WOB.

Compared with conventional pressure triggering, flow-by triggering decreased inspiratory WOB by approximately 5 to 10%. This finding supports previous reports of significant decreases in imposed WOB with tracheal pressure triggering compared with conventional pressure and flow-by triggering,⁶ and with flow-by triggering compared with conventional pressure triggering.⁵ Although we observed statistically significant differences between flow-by and conventional pressure triggering, the differences were small and probably not clinically significant. Flow-by triggering appears to be an improvement over conventional pressure triggering but does not result in clinically significant decreases in WOB imposed by the breathing apparatus (ETT plus ventilator)⁸ and, thus, does not decrease the total WOB as much as tracheal pressure triggering does.

The inability of a ventilator to meet peak inspiratory

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**METHOD OF TRIGGERING:**

<table>
<thead>
<tr>
<th>TRACHEAL</th>
<th>FLOW-BY</th>
<th>CONVENTIONAL</th>
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<tr>
<td>$V_i$ (L/sec)</td>
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<td>$V_T$ (L)</td>
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<tr>
<td>$P_{ew}$ (cm H₂O)</td>
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<tr>
<td>$P_{pl}$ (cm H₂O)</td>
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**Figure 4.** Airway pressure change measured at the Y-piece (Paw) and at the pleural space (Ppl) during spontaneous breathing with the demand-flow system of a ventilator triggered by tracheal pressure, flow (flow-by triggering), or conventional pressure with the same peak inspiratory flow rate demand ($Vi$) and tidal volume ($V_T$). Note that decreases in Paw and Ppl were greater with triggering by conventional pressure and flow than with tracheal pressure. A pressure support ventilation-like effect occurred only with tracheal pressure triggering, as can be seen by the airway pressure change measured in the Y-piece, that is, a positive airway pressure of approximately 15 cm H₂O was applied at mid-inhalation (dotted line).
The respiratory system may explain why WOB is higher with conventional pressure triggering than it is when the inspiratory demand-flow system is triggered by moving the sensor closer to the respiratory muscles. We contend that this may be true for flow-by triggering as well, and that the way to decrease ventilator insensitivity and improve the patient-ventilator interaction would be to trigger the system closer to the origin of respiratory effort—that is, at the carinal end of the ETT.

The clinical applicability of using tracheal pressure to trigger the ventilator may be hampered by the need for a pressure-measuring catheter at the carinal end of the ETT—such a small-diameter catheter may become occluded by secretions. This could be prevented by pulsing small volumes of air at regular intervals from the ventilator through the catheter and routinely monitoring the catheter for patency (watchdog system). If an occlusion were detected, an automatic default mode would be activated and the demand-flow system would be temporally triggered at an alternative site, such as the exhalation limb of the breathing circuit. After the occlusion was cleared, the microprocessor could verify patency and restore sensing/triggering to the carinal end of the ETT.

Inserting a catheter inside the ETT can also impair air flow and increase airway resistance, particularly with a small-diameter ETT (e.g., in pediatric patients). An alternative is an ETT with a catheter embedded in its sidewall (Hi-Lo Jet Orotracheal Tube, NCC-Mallinckrodt, Argyle, NY), which opens at the carinal end. Alternatively, retracheal pressure from the carinal end of the ETT may be continuously calculated without a catheter. The reliability of this method depends on knowing respiratory coefficients and airway pressure and flow rate at the Y-piece of the ventilator breathing circuit.

The PTP has been proposed as an estimate of metabolic oxygen consumption of the respiratory muscles and parallels WOB almost perfectly. Physiologic WOB normally ranges from approximately 0.3 to 0.6 J/L and the PTP/breath ratio, accordingly, from approximately 3 to 5 cm H₂O/s. The direct relationship between WOB and the PTP/breath ratio may have future implications. In conditions of increased airway resistance or increased inspiratory flow rate demand, when the change in Ppl is much greater than normal, negative Ppl may not simultaneously manifest as air movement, and no WOB would be detected. This isometric muscle contraction expends energy that will not be accounted for in WOB but will be in the PTP/breath ratio, because it integrates pressure change over time. Further study is needed to confirm this hypothesis.

We wondered whether decreasing the WOB by triggering the ventilator at the carinal end of the ETT was unique to the ventilator used in the study (Puritan-Bennett 7200ae). Therefore, WOB measurements and airway pressure waveforms for two other commonly used ventilators (model SV 900 C, Siemens, Danvers, Mass, and model 6400ST, Bird, Palm Springs, Calif) were tested under the same conditions. The results were essentially the same, including the PSV-like effect with tracheal pressure triggering. Based on current ventilator design, this phenomenon will likely occur with other ventilators as well.

In summary, compared with conventional pressure and flow-by triggering, triggering the ventilator at the carinal end of the ETT significantly decreases imposed WOB. Triggering the ventilator and controlling airway pressure at the carinal end of the ETT may decrease imposed WOB essentially to zero. Further study is warranted to differentiate the influences of these two mechanisms on WOB and to determine implications for future ventilator design. Clinical trials may show that triggering at the carinal end of the ETT is especially suitable for pediatric patients, in whom imposed WOB may be a major portion of the total WOB.

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