Pressure Support Compensation for Inspiratory Work due to Endotracheal Tubes and Demand Continuous Positive Airway Pressure*

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We evaluated the use of pressure support to compensate for the added inspiratory work of breathing due to the resistances of endotracheal tubes and a ventilator demand-valve system for continuous positive airway pressure (CPAP). A mechanical model was used to simulate spontaneous breathing at five respiratory rates through 7-mm, 8-mm, and 9-mm endotracheal tubes with and without a ventilator demand CPAP circuit. Added work was measured as the integral of the product of airway pressure and volume during inspiration. Additional work was a function of the tube's size, and each 1-mm decrease in the tube's diameter resulted in a 67 to 100 percent increase in work. Adding the ventilator CPAP circuit further increased work and was responsible for 30 to 50 percent of the total work resulting from a tube and CPAP circuit together. Pressure support was added to a level at which net work on the airway was zero, and a relationship between mean inspiratory flow (Vt/Ti) and the optimal level of pressure support was established for each endotracheal tube. The inspiratory work of breathing was then measured in normal subjects breathing with and without each endotracheal tube plus the demand CPAP circuit. Work per liter of minute ventilation due to the endotracheal tube and CPAP circuit was increased from 34 to 40 percent over levels measured while breathing through an open airway. For each endotracheal tube and Vt/Ti, a level of pressure support (range, 2 to 20 cm H2O) was found which eliminated added work in the spontaneously breathing subject. This level correlated well with that predicted from the data derived using the mechanical model. We conclude that when adjusting for an endotracheal tube's diameter and Vt/Ti, pressure support can be used to compensate for the added inspiratory work due to artificial airway resistances.

When an intubated patient breathes spontaneously through an intermittent mandatory ventilation (IMV) or demand continuous positive airway pressure (CPAP) ventilator circuit, both the resistance of the endotracheal tube and the ventilator circuit can contribute to the inspiratory work of breathing. The level of this additional work increases as the diameter of the endotracheal tube decreases and minute ventilation increases. Increased inspiratory work can contribute to respiratory muscle fatigue and interfere with successful weaning from mechanical ventilation.

Pressure support is a mechanical ventilator option which applies a predetermined amount of positive pressure to a patient's airway during the inspiratory phase of any spontaneous breath while in the CPAP or IMV mode. It has been proposed that pressure support may be used to compensate selectively for the increased inspiratory work due to breathing through an endotracheal tube and ventilator circuit; however, guidelines for use of pressure support for this purpose are not available. The intention of this study was to determine whether pressure support can compensate for the added inspiratory work due to breathing through endotracheal tubes and a ventilator demand-valve gas delivery system and to establish guidelines for its use.

Materials and Methods

Mechanical Model of Lung and Computation of Inspiratory Work

A reciprocating pump (Harvard Apparatus Co) was used as a mechanical model to simulate a patient's spontaneous breathing effort (Fig 1A). The "mouth" of this model was connected to an endotracheal tube alone or to endotracheal tube and a ventilator demand CPAP circuit. Air flow (V) was measured proximal to the endotracheal tube using a screen pneumotachygraph (Electronics for Medicine, adult-size) which was calibrated to flows of 0 to 1.5 L/s. Volume (V) was integrated from the airflow signal using a respiratory integrator (Hewlett-Packard 8815A). Airway pressure (Paw) was measured between the pneumotachygraph and endotracheal tube with a pressure transducer (Validyne DP45).

Inspiratory work was computed as the integral of the product of Paw and V during inspiration. Inspiratory work measured when Paw was negative represented work done by the simulated respiratory system (Wss). Inspiratory work measured during times of positive Paw represented work done on the respiratory system by the Ventilator (Wv). Net airway work (Wn) was defined as Wss minus Wv. Airway pressure, flow, volume, and work were recorded on a four-channel time-based strip-chart recorder (Hewlett-Packard 7754A). Inspiratory work per liter of ventilation (W/L) and mean inspiratory flow (Vt/Ti) were calculated as the mean of ten cycled breaths during each condition of measurement.

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of approximately 1:2 (actual $V_{T}/T_{I}=0.38$, 0.54, 0.64, 0.74, 0.83 L/s, respectively). At each respiratory rate, work was measured with (1) an open airway, (2) each size of endotracheal tube alone, and (3) each size of endotracheal tube plus the ventilator circuit.

For each condition of respiratory rate and endotracheal tube size, pressure support was added with each ventilator. When the pressure-support option is selected with the Puritan-Bennett 7200 ventilator, it is operative during the inspiratory phase of any spontaneous breath. When inspiratory effort is sensed as a negative deflection of Paw, pressure support is activated. The target Paw is the sum of the positive end-expiratory pressure (PEEP) and the set pressure support. Pressure support is terminated if Paw exceeds the target Paw by 1.5 cmH$_{2}$O or when inspiratory flow is 5 L/min or less. Pressure support can be applied over a range of 0 to 30 cmH$_{2}$O in increments of 1 cmH$_{2}$O.

Without pressure support, there is added work to the respiratory system (Waw is positive) due to the endotracheal tube and ventilator circuit resistance (Fig 2A). As pressure support is increased, Wns decreases, and Wv increases. We reasoned that the optimal level of pressure support was that level at which the Waw was equal to zero ($W_{ns}=W_{v}$) (Fig 2B). With higher levels of pressure support, Wns is further decreased and Wv increased, resulting in most of the work on the airway during inspiration being done by the ventilator (Waw is negative), as in standard pressure-cycled mechanical ventilation (Fig 2C).

With each condition of inspiratory rate and tube size, the pressure support was increased until the net Waw was calculated as zero. A linear relationship was established between this optimal level of pressure support and the $V_{T}/T_{I}$ for each endotracheal tube and ventilator using the method of least squares.

**Subject's Work and Pressure Support**

To determine the usefulness of the relationship of pressure support and $V_{T}/T_{I}$ derived from the mechanical model, transpulmonary inspiratory work was measured in four normal subjects. Each subject was trained to breathe at a $V_{T}$ of 500 ml at rates of 15, 25, and 35 breaths per minute with I:E ratios of approximately 1:2. Throughout the study, subjects monitored volume using an oscilloscope (Techtronix 5113) which displayed the integrated flow signal. Respiratory rate and I:E ratio were held constant with the aid of a metronome. Each subject breathed through the same circuit as was used as in the first part of the study (Fig 2B). In addition, esophageal pressure (Pes) was measured using an esophageal balloon$^5$. A 10-cm latex balloon attached to a perforated polyethylene catheter was positioned transnasally into the esophagus and filled.
with the appropriate volume of air. Subjects were seated in an upright position and breathed through a mouthpiece into the circuit with an open glottis and occluded nares.

Esophageal pressure, airway flow, and volume were recorded simultaneously, and VT/Ti was calculated as the mean of ten breaths. Inspiratory work done by the subject on the lung and airway was measured as the integral of the area enclosed by the plot of Pes and pulmonary volume during inspiration. The beginning of inspiration was defined as the point at which either inspiratory flow began (when Paw = 0) or when the sign of the Paw became negative prior to inspiratory flow (during resistive breathing). Inspiratory work per liter of ventilation (Waw/L) was calculated from the pressure-volume curves of ten representative breaths during each condition of measurement. At each respiratory rate, subjects breathed through a mouthpiece alone and through each of the three endotracheal tubes plus the ventilator CPAP circuit (CPAP = 0). For each tube size and level of mean inspiratory flow, pressure support was increased from zero in 2-cm H2O increments up to 6 cm H2O above the level predicted by the data from the mechanical lung.

**RESULTS**

**Mechanical Model**

The net added inspiratory work (Waw) increased progressively with decreasing size of the endotracheal tube and with increasing VT/Ti (Fig 3). Each 1-mm decrease in the tube's diameter resulted in a 67 to 100 percent increase in work. Adding the ventilator circuit increased the work further. The proportion of added work due to the endotracheal tube alone, when compared to the added work for the tube and ventilator together, was a function of the tube's size. On average, a 9-mm tube contributed 50 percent of the total added work, with 8-mm and 7-mm tubes contributing 60 and 70 percent, respectively.

**Pressure Support**

The net additional Waw decreased progressively with increasing pressure support (Fig 4). The optimal level of pressure support (resulting in Waw = 0) was plotted as a function of VT/Ti for each tube size for each of the three ventilators tested. A linear regression was fitted through these points for each tube size (Fig 5). There was a high level of correlation between optimal pressure support and VT/Ti. In each condition of tracheal tube size and VT/Ti, there was never more than a 2-cm H2O variation in optimal pressure support among the three ventilators tested.

**FIGURE 3.** Net additional work (Waw) to mechanical respiratory system model breathing through 7-mm, 8-mm, and 9-mm endotracheal tubes (ETT) alone (open bars) and through endotracheal tubes and ventilator circuit (CPAP = 0; pressure support = 0) together (hatched bars) at five respiratory rates.

**FIGURE 4.** Net additional work by mechanical respiratory system (positive Waw) due to endotracheal tube (ETT) and ventilator circuit with increasing pressure support for 9-mm, 8-mm, and 7-mm endotracheal tubes at respiratory rate of 20/min and VT of 0.5 L.
Subject's Work and Pressure Support

Figure 6 shows the mean W/L for the four subjects as a function of the endotracheal tube's size and Vt/Ti. During breathing by mouthpiece, the mean W/L increased from 0.024 kg-m (range, 0.013 to 0.031 kg-m) at a mean Vt/Ti of 0.38 L/sec to 0.030 kg-m (range, 0.022 to 0.040 kg-m) at a mean Vt/Ti of 0.68 L/sec. The endotracheal tube and ventilator circuit increased work significantly compared with mouthpiece breathing, and this increase ranged from 54 percent (0.013 kg-m/L) with a 9-mm tube and mean Vt/Ti of 0.38 L/sec to 240 percent (0.072 kg-m/L) with a 7-mm tube and mean Vt/Ti of 0.68 L/sec.

Figure 7. Plot of change in PES and pulmonary volume for subject 3 during spontaneous breathing (rate = 25/min; VT = 0.5 L). Data points represent measurements made at 0.1-s intervals during subject's breath. Solid lines and broken lines trace periods of inspiration and expiration, respectively. Hatched area signifies inspiratory work. Plots are shown for representative respiratory cycles while breathing through mouthpiece (A), through 7-mm endotracheal tube and ventilator circuit without pressure support (B), and through 7-mm endotracheal tube and ventilator circuit with level of pressure support (6 cm H2O) sufficient to result in W/L equivalent to that during mouthpiece breathing (C). Inspiration is denoted by positive changes in Pes.
At each respiratory rate, each endotracheal tube, together with the ventilator circuit, increased the inspiratory work significantly when compared with mouthpiece breathing. This added work increased progressively with increased inspiratory flow demand and decreasing tube size, as predicted by observations with the mechanical lung.

For each condition of tube size and respiratory rate, increasing pressure support decreased the inspiratory work. The optimal pressure support was at that level at which $W_{I}/L$ was closest to that while breathing through a mouthpiece (Fig 7). The optimal level of pressure support was plotted as a function of $V_{T}/T_{I}$ for each subject breathing through each endotracheal tube and was remarkably similar to that pressure support predicted by the relationship derived using the mechanical breathing model as shown in Figure 8.

The peak change in Pes also was evaluated as an indicator of the patient's effort. With pressure support equalling zero, this also increased with decreasing endotracheal tube diameter and with increased $V_{T}/T_{I}$. At those levels of pressure support which optimally compensated for added measured inspiratory work, peak change in Pes was similar to that while breathing through a mouthpiece alone (Fig 9).

**Discussion**

This study confirms that endotracheal tubes and a ventilator demand CPAP system can markedly increase the inspiratory work of breathing. The additional work rate ($W_{I}/L$) due to these added resistances increases with increased flow demand and decreased internal diameter of the tube. Pressure support can be used to compensate for this added work when the level is adjusted for the endotracheal tube's diameter and mean inspiratory flow.

The effect of the endotracheal tube's size on airway resistance and work of breathing is substantial. Bold and associates have reported that every 1-mm decrease in the endotracheal tube's diameter results in an increase in work of 34 to 154 percent, depending on the respiratory rate and tidal volume. In the mechanical-lung phase of this study, our findings were similar, with each 1-mm change in the tube's diameter resulting in a 67 to 100 percent increase in $W_{I}/L$. The effect of demand CPAP systems on work varies among ventilators. Katz et al have shown that the Puritan-Bennett 7200 ventilator circuit results in 10 to 40 percent increase in additional inspiratory work, depending on inspiratory flow. Consistent with these studies, we found that the relative contributions to added work of an endotracheal tube and the ventilator circuit in this study were a function of tube size, with the proportion of work due to the endotracheal tube ranging from approximately 50 percent for a 9-mm tube to 70 percent for a 7-mm tube.

Inspiratory work per liter is a good measure of the mechanical properties of the lungs and airways in patients with respiratory failure. Peters et al have suggested that mechanical ventilation is necessary when $W_{I}/L$ is greater than 0.18 kg-m/L and that ventilator independence is associated with $W_{I}/L$ of less than 0.08 kg-m/L. We have found that patients requireing prolonged mechanical ventilation had a mean $W_{I}/L$ of 0.090 kg-m/L when they were successfully weaned. During unassisted spontaneous inspiration, there is negative airway pressure generated to overcome the resistances of the demand valve, ventilator circuit, and endotracheal...
tube. This results in additional inspiratory work. In the present study of normal subjects, the \( W_t/L \) during breathing by mouthpiece (range, 0.013 to 0.040 kg-m) was comparable to published "normal" values.\(^\text{13} \) For the group of subjects, the mean increase in work due to both an endotracheal tube and demand CPAP together ranged from 0.013 to 0.072 kg-m/L, depending on tube size and VT/TI. This represented a 54 to 240 percent increase over baseline values. Since the VT/TI of patients being weaned from mechanical ventilation covers a range which was simulated in this study,\(^\text{14,15} \) increases in work of these magnitudes would be expected in clinical practice. Clearly, this degree of added work could affect the success or failure of a weaning trial. This may have particular impact on patients with either marginal respiratory muscle strength or those who already have a high level of respiratory work due to pulmonary parenchymal disease.

Pressure-support ventilation has been suggested as a method by which to compensate for the increase in inspiratory work produced by endotracheal tubes and demand valve CPAP circuits;\(^\text{16} \) however, there has been no previous documentation which validates this proposed clinical application. Our findings indicate that pressure support may be useful for this purpose.

We observed that as pressure support is increased, the added inspiratory Waw produced by the resistance of the endotracheal tube and demand valve circuit decreased. For each endotracheal tube, linear relationships between the pressure support needed to result in zero Waw and mean inspiratory flow were established. For each combination of endotracheal tube and mean inspiratory flow rate, these relationships accurately predicted a level of pressure support which effectively eliminated added transpulmonary inspiratory work due to airway resistance in the spontaneously breathing subject. Thus, a condition of breathing by mouthpiece without an endotracheal tube or ventilator circuit was simulated. Since the optimal pressure support is that level at which Waw = 0, a method of bedside integration of air flow and distal endotracheal tube airway pressures to calculate Waw would allow accurate titration of pressure support. When using a Puritan-Bennett 7200 ventilator pressure-support system, pressure support can be selected using the regressions relating optimal pressure support to VT/TI derived in this study.

We believe that pressure support may be useful in weaning some patients with marginal ventilatory mechanics from mechanical ventilation. Weaning often involves spontaneous breathing in a CPAP or IMV mode. By using pressure support to compensate for the resistance of only the endotracheal tube and demand CPAP circuit associated with these spontaneous breaths, the success or failure of weaning would be governed more by the patient's respiratory mechanics than that of the artificial airway. In addition, studies in patients recovering from respiratory failure have suggested that patients subjectively tolerate pressure support very well and may prefer pressure support to other modes of mechanical or spontaneous ventilation.\(^\text{17,18} \)

Although we performed these studies using only one ventilator manufacturer's pressure-support system, we nevertheless believe that the principles we have discussed will apply to other available ventilator pressure-support systems as well; however, variability in factors such as the effectiveness in achieving and maintaining the set level of pressure support and the mechanism by which pressure support is terminated at the end of inspiration will affect the particular relationship be-
tween optimal pressure support and Vt\textbackslash T1 as derived in this study. For instance, a ventilator circuit with higher resistance would require higher levels of pressure support at a given Vt\textbackslash T1 and endotracheal tube diameter. Therefore, the specific regressions derived in this study for selecting the optimal level of pressure support may not apply to other ventilator systems.

Positive airway pressure is often used during weaning trials to maintain arterial oxygen pressure and functional residual capacity.\textsuperscript{19,20} This study was carried out at ambient airway pressure (CPAP = 0), and the effect of varying levels of positive airway pressures on the requirement for pressure support was not evaluated; however, there are minor changes in airway pressure-volume relationships when the level of CPAP is increased on the Puritan-Bennett 7200 ventilator.\textsuperscript{3} If pressure support functions consistently at various levels of CPAP as well, the relationship of pressure support to Vt\textbackslash T1 reported in this study should apply.

In summary, pressure support can be used to overcome the resistances of endotracheal tubes and ventilator circuits and compensate selectively for the added inspiratory work due to these resistances. The level of pressure support must be adjusted according to the endotracheal tube’s size and inspiratory flow rate. By using pressure support in this way, a patient’s ability to maintain spontaneous breathing may be better assessed, and successful weaning may be facilitated.

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REFERENCES
3 Katz JA, Kraemer RW, Gjerde GE. Inspiratory work and airway pressure with continuous positive airway pressure delivery systems. Chest 1985; 88:519-26
12 Fiastro JF, Campbell SC, Shon BY, Habib MP. Comparison of standard weaning parameters and mechanical work of breathing in mechanically ventilated patients (abstract). Am Rev Respir Dis 1986; 133:A122
17 MacIntyre NR. Respiratory function during pressure support ventilation. Chest 1986; 89:577-83
20 Quan SF, Falltrick RT, Schlobohm RM. Extubation from ambient or expiratory positive airway pressure in adults. Anesthesiology 1981; 55:53-6