Flow Resistance of Expiratory Positive-Pressure Systems*

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We measured the flow-resistance of five commercially available 10 cm H2O expiratory positive-pressure (EPP) valves (n=5 per valve type) at bias flows of between 0 and 2,000 ml/s. We found that individual valves of each type and manufacturer functioned similarly. Different valve types, however, functioned differently: with one type, system pressure was higher than rated (p<0.05), and with another type, system pressure was significantly flow-de-

pendent (p<0.01). The remaining types of valves had no flow-resistive properties and maintained a system pressure of 10 cmH2O. We conclude that system pressure is not similar in all continuous positive airway pressure (CPAP) systems using bias flow and EPP valves. The work of breathing imposed by CPAP circuits will be increased in systems whose EPP valves have flow-dependent properties. (Chest 1988; 94:788-91)

Continuous positive airway pressure (CPAP) is often used as an adjunct to treatment of acute hypoxemic respiratory failure. Indeed, Venus et al.1 adequately supported patients in acute hypoxic respiratory failure with CPAP and increased FIO2 without positive-pressure ventilation. Similarly, CPAP often is used as part of the process of weaning patients from artificial ventilation. Because the work of breathing may increase with CPAP,2 respiratory muscle fatigue and alveolar hypoventilation may develop. The causes of increased work of breathing imposed by CPAP circuits include inhalation against a falling airway (system) pressure and active exhalation necessitated by a high-flow resistant expiratory positive-pressure (EPP) valve.3,5

When CPAP is delivered to a patient receiving intermittent mandatory ventilation (IMV), a demand valve system often is used to maintain system pressure during spontaneous breathing.6 In the demand-valve system, the pressure in the system must decrease before flow will be delivered to the spontaneously breathing patient. This obligatory decrease in airway pressure during inspiration inevitably increases the work of breathing.7 The greater the decrease in inspiratory airway pressure, the greater the work required to ventilate. An alternative method to maintain system pressure during CPAP uses continuous flow (bias flow) through the system. Continuous-flow CPAP circuits attempt to maintain a constant system pressure during spontaneous breathing by delivering a bias flow of gas from a source both to the patient and through the ventilatory circuit such that even during inspiration, source gas exits through the EPP valve. If bias flow from a source is constant, then breathing will alter the rate of flow through the EPP valve. For example, during inspiration flow through the EPP valve will decrease as more bias flow is diverted to the patient, while during exhalation, flow through the EPP valve will exceed bias flow. If an ideal valve is changed for one that demonstrates flow-dependent properties, then system pressure will vary with the phase of ventilation. During inspiration, as flow through the EPP valve decreases, system pressure also will decrease. The patient must generate a greater fall in pleural pressure to equal the fall in system pressure. This additional work of inspiration is schematically represented in the volume-pressure relationship as an increase in area usually ascribed to overcoming resistance (Fig 1). However, such increased work is more appropriately considered an external work load and is elastic rather than resistive in nature.8 Similarly, if system pressure rises during exhalation, resistance to exhalation also will increase. The net result may be a significant increase in the work of breathing. In this study, we measured the pressure-flow relationship of various commercially available 10 cmH2O EPP valves commonly used in CPAP circuits. Among the different models, we found significant differences in the pressure-flow relationship which may be clinically significant.

Methods

We tested five different types of commercially available 10 cm H2O EPP valves: the Boehringer (Boehringer Laboratories Inc, Wynnewood, PA); the adjustable Instrumentation Industries (II) (Instrumentation Industries, Bethel Park, PA); the fixed bore II, adjustable Respironics (Respironics, Inc, Monroeville, PA); and the Vital Signs (Totowa, NJ). Five valves of each type were studied. The Boehringer valve operates by the gravitational obstruction of a fixed

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orifice by a weighted steel ball. As system pressure exceeds the rated valve pressure (threshold pressure), the steel ball is displaced upward, increasing the valve orifice. The II valves are sealed to the orifices by a magnetic ring that resists displacement until the threshold pressure is reached. The adjustable II valve has a further mechanism that alters the resisting tension on the magnetic valve, so that different valve threshold pressures can be set. The Respironics and Vital Signs valves have a springload valve over the orifice; in the adjustable Respironics valve, the spring tension can be manually adjusted to vary the threshold pressure.

The experimental apparatus consisted of a flow generator, a port for pressure measurements, and a downstream EPP valve (Fig 2). Bias flow was generated from a compressed air source and varied by using two Downs flow generators (Vital Signs) arranged in parallel fashion. Absolute bias flow was measured using a pneumotachograph (Fleisch) interfaced to a differential pressure transducer (Validyne) calibrated to a large-bore rotameter (Fisher Scientific). System pressure was measured through a side port of the circuit tubing using a Statham 23-dB pressure transducer (Gould) calibrated by a mercury manometer. The system pressure (in centimeters of H2O) and bias flow (in milliliters per second) were recorded simultaneously on a polygraph (Gould). Using this circuit, each EPP valve was tested during gradually increasing, then decreasing, flow rates of 0 to 2,000 ml/s. For the adjustable EPP valves, the system pressure was adjusted to 10 cm H2O at a bias flow rate of 1,000 ml/s, the standard practice for setting such EPP valves in our respiratory therapy department. After all EPP valves had been tested, one valve of each type was retested using the same protocol to assess reproducibility of the system pressure measurements.

Statistical analysis within groups was performed using a repeated measures analysis of variance. When differences in system pressure between increasing and decreasing ramp bias flow were observed within a group, these two pressure-flow data sets were compared by a two-way analysis of variance. Between-group comparisons were made using a two-way analysis of variance. If significant differences were found, specific comparisons were made using a Student-Newman-Keuls test. Significance reports a probability value of less than 0.05.

RESULTS

The effect of bias flow on system pressure for all five types of EPP valves is shown in Figure 3. System pressure was highly reproducible among different valves of the same type. Also, system pressure displayed no measurable phase lag in reaching a steady-state pressure to abrupt changes in bias flow. With the adjustable II, the Vital Signs, and the adjustable Respironics valves, system pressure varied little over the range of flows studied and was not significantly different from 10 cm H2O. The Boehringer valves maintained a system pressure of 12.3 ± 1.0 cm H2O, which was significantly higher than 10 cm H2O. This higher system pressure may have been due to the marked oscillation in system pressure seen when the ball valve within the unit started to oscillate at flows above 500 ml/s (-4.9 cm H2O). There was significant hysteresis in the pressure-flow curve for the Vital Signs valves, such that during decreasing bias flow system pressure was as much as 2.7 cm H2O lower than at similar flows during increasing bias flow. With the fixed bore II valves, system pressure was significantly flow-dependent, such that as bias flow increased to >1,000 ml/s, system pressure increased in a linear fashion, reaching 17.0 ± 3.0 cm H2O at a flow of 2,000 ml/s.

DISCUSSION

Spontaneous breathing with CPAP improves arterial oxygenation in patients with acute hypoxemic respiratory failure. Similarly, CPAP systems are widely used to wean patients with hypoxemic respiratory failure from mechanical ventilation, such that as pulmonary dysfunction resolves, the level of CPAP is reduced. When patients are breathing on a CPAP
circuit, additional work of breathing may be created by the CPAP circuit owing to fluctuations in system pressure or overdistension of the lung at end-expiration. Although previous studies have shown that continuous-flow CPAP systems imposed less work of breathing than the demand-valve systems tested, no study has compared different EPP valves in a common CPAP circuit. Our study demonstrates that the type of EPP valve used in a continuous-flow CPAP system may influence the inspiratory work of breathing.

The work of breathing of a patient on a CPAP circuit has three components: elastic work, that necessary to overcome elastic forces resisting changes in lung volume; resistive work, that necessary to overcome the resistance of the endotracheal tube and airways; and the external work necessary to overcome the inspiratory decrease in system pressure (Fig 1). Hypoxemic respiratory failure is usually associated with a decrease in lung volume, which may decrease pulmonary compliance and increase airway resistance. If CPAP increases compliance by recruiting additional lung units, then the work of breathing may decrease. However, if the external work of breathing imposed by a CPAP circuit is increased by flow-dependent changes in system pressure, then any beneficial effect of CPAP on the work of breathing will be minimized. Thus, the clinical applicability of such a circuit may be limited.

In this study, only the fixed-bore II EPP valve demonstrated flow-dependence of system pressure. With the fixed-bore II valves, system pressure increased as flow increased to >1,000 ml/s (Fig 3). With all other EPP valve types, system pressure was independent of flow. If bias flow is kept greater than peak inspiratory flow, and the EPP valve functions independently of flow (acts as an ideal threshold valve), then system pressure will remain constant. The EPP valves that cause flow-dependence of system pressure will create two important negative effects. First, the level of EPP will increase as bias flow increases.

**Figure 3.** Relationship between system pressure (P cm H2O) and bias flow (V bias, ml/sec) for five models of 10 cm H2O expiratory positive-pressure (EPP) valves. Individual data points represent mean ± SE of five valves of each model. Solid circles are values during increased V bias, while open circles represent decreasing V bias. Note that the Instrumentation Industries (II) fixed-bore EPP valves increased P as V bias increased to >1,000 ml/s, the Vital Signs EPP valves demonstrated hysteresis, and the Boehringer EPP valves maintained p greater than 10 cmH2O at all V bias.

Flow Resistance of Expiratory Positive-pressure Systems (Pinsky et al)
Second, inspiration, by decreasing flow through the EPP valve, will also decrease system pressure, thus increasing the external work of breathing. Transient increases in inspiratory flow above source flow can be dealt with in a CPAP circuit by interposing a three-liter reservoir bag between the source flow and the patient. With the three-liter reservoir bag functioning as a volume capacitor for variable flow, source flows of 500 to 750 ml/s may be sufficient for many adult patients on CPAP. To the extent that bias flow is maintained constant by the insertion of a reservoir in the circuit, system pressure will be maintained constant even when flow-dependent EPP valves are used. Nevertheless, the reservoir bags available require significant decrease in inspiratory airway pressure to supplement bias flow and therefore cannot maintain system pressure. Even if a constant bias flow through the EPP valve were ensured, with the fixed-bore II EPP valve a large increase in system pressure occurred as bias flow increased to >1,000 ml/s (Fig 3). Thus, the actual system pressure of the CPAP circuit may not reflect the set pressure if bias flow exceeds the EPP valve’s threshold for resistance. Similarly, with the Boehringer EPP valves, system pressure exceeded 10 cmH₂O, although it was not flow-dependent. Our study did not include all commercially available EPP valves. However, among the types we did study, system pressure differed significantly. Thus, during CPAP it is necessary to monitor system pressure directly and not to assume that a factory-defined pressure threshold is accurate.

Recently, Banner et al. demonstrated significant flow-resistive properties of EPP valves in many commercially available ventilators. System pressure was flow-dependent to different degrees in many of the models they tested. Since the EPP valves tested in their study were integral to the ventilator, comparisons between theirs and our data would be difficult. However, qualitatively both studies demonstrate the flow-resistive potential of EPP valve systems. Thus, any respiratory apparatus used to maintain elevated airway pressure, whether separate from a mechanical ventilator or built into the ventilator circuitry, may fail to maintain constant system pressure, independent of bias flow.

In summary, in four of the five types of EPP valve system pressure in the CPAP circuit was not flow-dependent. If bias flow is higher than peak inspiratory flow and EPP valves without flow-dependence are used, the external work imposed by the CPAP circuit should be minimal. However, it is not enough to assume that a given type of EPP valve maintains system pressure at its reported level, system pressure must be adequately monitored.

REFERENCES

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