The flow-resistive characteristics of a variety of commercially available expiratory positive-pressure valve systems used to provide continuous positive airway pressure (CPAP) and positive end-expiratory pressure were evaluated. One flow-resistor and seven threshold-resistor expiratory pressure valve systems were set at 5, 10, 15, 20, and 25 cm H₂O of expiratory pressure, and sinusoidal exhaled flows peaking at 50, 100, and 200 L/min were directed through each valve at each level of expiratory pressure. The Siemens flow-resistor valve demonstrated the greatest deviation in pressure above set CPAP levels at peak flow rates of 100 and 200 L/min, which suggests high resistance to exhaled flow. The Vital Signs threshold-resistor valve demonstrated the least deviation in pressure from set CPAP levels at all rates of exhaled flow, which suggests low flow resistance. The Emerson and IMV Bird threshold-resistor systems resisted flow less than the BEAR-2 and the Puritan-Bennett MA-2 and 7200 inflatable-balloon threshold-resistor-like valve systems. These data suggest that threshold resistors may be classified as low-resistance or high-resistance types. Using only low-resistance threshold resistors for CPAP may minimize the incidence of barotrauma and other deleterious effects related to airway pressure.

**Expiratory pressure valves may be classified as threshold resistors and flow resistors.** A threshold resistor generates expiratory positive pressure (P) by applying a constant force (F) over a discrete surface area (SA). With such a device, exhaled gas passes freely through a wide orifice until airway pressure decreases to a preset level of expiratory positive pressure, at which time the valve abruptly closes and traps the remaining gas in the airways and parenchyma of the lungs. With a threshold resistor, P=F/SA. (Force is the critical factor; in reality, the balance of forces acting on the valve, and not pressure, opens and closes the valve.) A threshold resistor ideally should generate expiratory positive pressure without retarding flow by resistive means. In contrast, a flow resistor produces expiratory positive pressure by imposing an adjustable orifice resistance (R) to exhaled flow rate (V). Expiratory positive pressure varies inversely with the orifice size, assuming V is constant. Thus, the magnitude of the pressure generated is directly related to R. With such valves, P=RV (Fig 2). (This relationship is congruent only under certain laminar flow conditions and a given range of flow rates.) Both types of valves are used in ventilator circuits to regulate the level of expiratory positive pressure during continuous positive airway pressure (CPAP) with spontaneous ventilation and during positive end-expiratory pressure (PEEP) with mechanical ventilation.

In practice, resistance to exhaled V occurs with both types of valves. As a result, with many commercially available threshold or flow resistors, the level of expiratory positive pressure deviates from that set when exhaled V changes. Some threshold or flow resistors can produce very high airway pressures when exhaled V is high, as during coughing. Therefore, the incidence of barotrauma and deleterious cardiovascular effects may be increased by expiratory pressure-valve flow resistance.

A variety of valves are used clinically for threshold or flow resistors without sufficient understanding of the interaction between exhaled flow rate and airway pressure. We studied the effects of expiratory positive-pressure valve systems on airway pressure.

**Materials and Methods**

The ventilator systems used were the Siemens 900C (n = 3), BEAR-2 (n = 3), Puritan-Bennett MA-2 (n = 3) and 7200 microprocessor types (n = 3), IMV Bird (Bird-Products Corp.) (n = 3), and IMV Emerson (J. H. Emerson Co.) (n = 6; three newer and three older expiratory pressure valve models). For all ventilators the stock permanent-type expiratory pressure valve recommended by the manufacturer was used. These ventilators all generate CPAP by means of a demand valve or demand valve-like system. Three sets of gravity-dependent weighted-ball valves (Boehringer) calibrated at 5, 10, and 15 cm H₂O were attached to the expiratory limb of a standard reservoir-bag constant-flow (15 L/min) system to provide CPAP.

"Flow Resistance of Expiratory Positive-pressure Valve Systems (Banner et al)"

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Finally, three sets of nonadjustable, spring-actuated threshold resistor valves (Vital Signs) calibrated at 5, 10, 15, and 20 cm H2O were attached also to the expiratory limb of a reservoir-bag constant-flow (15 L/min) system, to provide CPAP.

The flow-resistive characteristics of the expiratory pressure valves were evaluated by using a bench model (Fig 3). An Emerson 3-FV volume-limited ventilator was modified to function as a spontaneously breathing patient and to mimic standardized controlled rates of sinusoidal exhaled flow directed through all CPAP systems. A standard 8-mm (inner diameter) endotracheal tube was connected to this model. Attached to the endotracheal tube was a pneumotachograph (Fleisch) connected to a differential pressure transducer (Gould-Statham PM15E) to measure V. Next, the ventilator CPAP system (expiratory pressure valve) to be studied was connected to the open end of the pneumotachograph. At the connection between the ventilator's "Y" piece and the pneumotachograph was a pressure tap attached to one sensing port of another differential pressure transducer (Gould-Statham PM131TC). The other pressure input for this transducer was placed distal to the exit orifice of the expiratory pressure valve. This transducer was used to measure the drop in pressure (ΔP) across the exhalation limb of the CPAP circuit. The two transducers were connected to an amplifier-recorder system (Grass Medical Instruments) and were used to measure V and ΔP, respectively. Previously, the calibration and the linearity of the pneumotachograph were determined at flow rates of 25, 50, 100, and 200 L/min.

Three rates of sinusoidal peak exhaled flow at 50, 100, and 200 L/min were directed through ventilator CPAP systems set at 5, 10, 15, 20, and 25 cm H2O of CPAP. (To generate 20 and 25 cm H2O of CPAP with the weighted-ball valves, a 10-cm H2O valve was attached in series with another 10-cm H2O and to a 15-cm H2O valve, respectively; however, we do not condone stacking these valves in clinical practice.) Since the spring-actuated, expiratory pressure valves are only available at the levels of 5, 10, 15, and 20 cm H2O, and since the company (Vital Signs) does not recommend stacking valves in series to generate higher expiratory pressures, measurements at 25 cm H2O were not obtained.

Normally, an adult can generate peak exhaled flow rates greater than 400 L/min during a cough. We empirically selected half of this amount as the maximal exhaled flow rate for our study in order to mimic intubated patients with compromised pulmonary function. Because of the endotracheal tube, the glottis cannot close normally as it does during coughing, and, thus, high intrapulmonary pressure and exhaled flow rate (400 L/min) are unlikely. In addition, compromised pulmonary function may compromise the peak exhaled flow rate. For these reasons, we estimated that a more reasonable figure for peak exhaled flow rate during a cough with endotracheal intubation would be about 200 L/min.

For all levels of CPAP and peak exhaled flow rates tested with each CPAP system, ΔP was measured by the differential pressure transducer on the exhalation limb of the breathing circuit (Fig 4). Each CPAP system (expiratory pressure valve) was tested five to ten times at each level of CPAP and each exhaled flow rate to confirm reliability and to perform statistical analyses. All data were processed by analysis of variance; p<0.05 was considered significant.

**RESULTS**

At all exhaled flow rates, all expiratory pressure valve systems increased expiratory positive pressure above the set level, some systems offering significantly more resistance to flow than others. The Siemens flow-resistor expiratory pressure valve caused the greatest deviations in pressure above most levels of CPAP at 50 L/min and for all levels of CPAP at 100 and 200 L/min of exhaled flow rate (p<0.05) (Table 1). The Vital Signs multiple spring-actuated valves demonstrated the lowest deviations in pressure at all exhaled flow rates at

**Figure 1.** Example of threshold-resistor expiratory pressure valve (Emerson), where expiratory positive pressure (P) is proportional to force (F) in this case, hydrostatic F exerted by water in column applied over exhalation outlet surface area (SA) (SA = πr²/4) of diaphragm. In this example, F = 0.96 newtons and SA = 0.00096 sq m; since 1000 newtons/sq m is approximately 10 cm H2O of pressure, valve is set to generate P of 10 cm H2O. Left, At beginning of exhalation, when P generated by airway pressure is greater than F exerted by valve, F in equilibrium results, diaphragm raises, and exhalation occurs. Right, At end of exhalation, when F generated by airway pressure is less than F exerted by valve, diaphragm descends, occluding exhalation outlet.

**Figure 2.** Adjustable-size, variable-orifice, flow-resistor expiratory pressure valve, where expiratory positive pressure (P), denoted by plus sign, is proportional to resistance (R) times gas flow rate (V) passing through valve. R varies inversely with orifice size (the narrower the orifice, the greater R, and vice versa). If R was set to equal 10 cm H2O/L/sec and the exhaled V was 1 L/sec, then at that moment during exhalation, P would equal 10 cm H2O. Doubling of V would double P, and vice versa. (True only if R to flow is constant over all ranges of flow, ie, straight line on pressure-vs-flow graph.)
5, 10, 15, and 20 cm H2O of CPAP. The IMV Bird and older Emerson valves demonstrated lower deviations in expiratory pressure compared with the inflatable balloon expiratory pressure valves of the BEAR-2, MA-2, and 7200 ventilators at all peak exhaled flow rates and CPAP levels. At each level of CPAP, as the exhaled flow rate increased, deviations in expiratory positive pressure were progressively disparate among some brands of valves (Table 1).

**FIGURE 3.** Continuous positive airway pressure (CPAP) (expiratory pressure valve) system attached to pneumotachograph and then to mechanical model of spontaneously breathing patient. Pneumotachograph measures sinusoidal rates of exhaled flow, and differential pressure transducer (DP) measures drop in pressure (ΔP) across exhalation limb of breathing circuit.

5, 10, 15, and 20 cm H2O of CPAP. The IMV Bird and older Emerson valves demonstrated lower deviations in expiratory pressure compared with the inflatable balloon expiratory pressure valves of the BEAR-2, MA-2, and 7200 ventilators at all peak exhaled flow rates and CPAP levels. At each level of CPAP, as the exhaled flow rate increased, deviations in expiratory positive pressure were progressively disparate among some brands of valves (Table 1).

**FIGURE 4.** Drop in pressure across exhalation limb of breathing circuit (ΔP) and exhaled flow rate (V̇) waveforms for two of expiratory pressure valve systems tested. Continuous positive airway pressure (CPAP) was set at 10 cm H2O for both systems. When same rate of sinusoidal exhaled flow was directed through each, peak expiratory positive pressures differed substantially, which suggests differences in valve flow resistance.

**FIGURE 5.** Ideal threshold resistor (solid line) maintains constant expiratory airway pressure with variation in exhaled flow rate. Ideal flow resistor (dashed line), when set to fixed orifice size, maintains constant resistance independent of exhaled flow rate and predisposes system to deviations in expiratory positive pressure secondary to effects of exhaled flow rate. Pressure-flow characteristics of two expiratory pressure valves, ie, Puritan-Bennett 7200 (inflatable balloon) (dash-dot line) and Vital Signs (multiple spring-actuated constant force) (dotted line) valves are shown. Figure represents peak increases in expiratory pressure (ie, pressure drop across exhalation valve) above set 10 cm H2O of CPAP level at three peak sinusoidal exhaled flow rates. Some valves demonstrated higher resistance compared with others. Pressure-flow characteristics of threshold resistors seem to fall within continuum between ideal threshold resistor and ideal flow resistor. Those approaching pressure-flow characteristics of ideal threshold resistor are preferable (Table 1).
Table 1—Pressure Drop across Exhalation Limb of CPAP Circuit or Peak Increases in Expiratory Pressure above Five Set Levels of CPAP at Three Rates of Sinusoidal Exhaled Flow with Different Expiratory Pressure Valve Systems

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<tr>
<th>Peak Exhaled Flow, L/min</th>
<th>CPAP Setting, cm H2O</th>
<th>Siemens</th>
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<th>MA-2</th>
<th>7200</th>
<th>Boehringer</th>
<th>IMV Bird</th>
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*Values are means ± SD.
†Significantly highest pressure compared with others at same sinusoidal exhaled flow rate and level of CPAP (p<0.05).
‡Significantly lowest pressure compared with others at same sinusoidal exhaled flow rate and level of CPAP (p<0.05).

DISCUSSION

With CPAP during exhalation, expiratory pressure valves of many breathing circuits used today resist flow, which substantially increases pressure during exhalation.12 Consider an expiratory pressure valve exerting 10 cm H2O of expiratory positive pressure with a flow resistance of 15 cm H2O/L/sec (assumed linear over a given range of flow rates); such a valve would increase airway pressure to 25 cm H2O at an exhaled flow rate of 1 L/sec (60 L/min). Should the patient cough or exhale rapidly, airway pressure may go as high as 60 or 70 cm H2O.12 Indeed, in our study, expiratory pressures were twice this magnitude under some conditions. The change in pressure in the respiratory tract likely could be much greater than the change in pressure we observed, since we measured pressure distal to the endotracheal tube. Furthermore, changes in airway pressure above the CPAP level would vary inversely with the endotracheal tube diameter and directly with respiratory tract resistance. For example, in a patient who coughs while receiving 25 cm H2O CPAP from the 7200 ventilator, distal airway pressure may increase far in excess of our measurements. Such pressure increases may not be widely appreciated by the majority of clinicians caring for mechanically ventilated patients.

A threshold resistor should maintain the set expiratory positive pressure regardless of variations in exhaled flow rate,13 as opposed to a CPAP system with a flow resistor, with which deviations in airway pressure occur when the physiologic exhaled flow rate or the gas flow rate directed through the CPAP system changes (Fig 5).13 All threshold resistor valves that we tested functioned imperfectly; ie, resistance to exhaled flow rate varied widely among them. These observations are consistent with data14 suggesting that threshold resistors may be classified as high-flow or low-flow resistant types (Fig 5).12,14 Low-flow resistant threshold resistors are preferable when CPAP and PEEP are indicated and may predispose to a lower incidence of pulmonary barotrauma, cardiovascular embarrassment, and increased intracranial pressures.

Mechanically, the Siemens 900 C "scissor" valve operates as a flow resistor. The hinged clamp design of this valve narrows the area of the exhalation orifice. The narrower the orifice, the greater the resistance to flow; hence greater back pressure (ie, CPAP level) is generated in the breathing circuit. As mentioned earlier, since P=RV with a flow resistor, one could predict a priori that as the exhaled flow rate increases, expiratory airway pressure must increase if R is constant (Fig 2 and 5). Our findings support this relationship; as peak exhaled flow rate increased, proportional increases in the peak expiratory pressure occurred above all set CPAP levels with the Siemens flow resistor valve (Table 1). This flow resistor seemed to demonstrate greater expiratory resistance than any threshold resistor tested at most levels of CPAP at 50 L/min and for all CPAP levels at 100 and 200 L/min peak exhaled flow rates.

To explain why flow resistance varied among threshold resistors requires a detailed analysis of the mechanism by which the valve applies force to obstruct the exhalation outlet. The pressure that the patient must generate to exhale through the outlet...
equals the force applied by the valve divided by the effective surface area of the valve, plus the pressure required to overcome the resistance to exhaled flow through the outlet. At the onset of exhalation, the obstructing force must be immediately displaced away from the exhalation valve to allow unimpeded free-flowing exhalation. At the end of exhalation, the obstructing force exerted by the valve just exceeds the force generated by airway pressure; the exhalation outlet is sealed shut, and exhalation ceases.

A threshold resistor that does not vary the obstructing force applied during the respiratory cycle may be defined as a “passive” threshold resistor. Such a valve acts as a rectilinear mechanical system with one degree of freedom (see appendix, equation 1). Different designs of passive threshold resistors emphasize different terms of equation 1. For example, the gravity-dependent valves (water-column, submerged-outlet, and weighted-ball valve) develop force from the third term, mass times acceleration (ma) (acceleration [a] is provided by gravity), with negligible contribution from the other two terms.

In a spring-loaded valve, the spring constant of the valve system times the distance of compression or extension of the valve face from its natural resting position (KI) is the dominant term. With the Vital Signs valve, F is exerted by the bending action of multiple springs attached to a movable disk. F is not generated by compression or tension on the springs, as with a conventional single-spring valve, but by their bending. A unique feature of this design is that the F exerted appears to remain relatively constant with increasing displacement from the resting position. Thus, as exhaled flow rate increases, the valve opens further to accommodate the higher flows but does not change the F applied during exhalation. The net effect of a valve offering a larger exit area for exhalation while exerting constant F is to minimize large increases in expiratory airway pressure and, thus, act as a low-resistance threshold resistor. Indeed, it is probably for this reason that the Vital Signs expiratory pressure valves demonstrated the least deviation in expiratory pressure above the CPAP levels at all rates of exhaled flow.

An inflatable balloon valve that uses a pressurized balloon to obstruct the exhalation outlet may be considered an “active” threshold resistor-like device. The analysis of this design is more complex because the balloon acts as a miniature lung with its own dynamic characteristics, including flow resistance, compliance, and internal pressure. The obstructing force applied by the balloon can also be expressed mathematically (see appendix, equation 2).

Force exerted by the balloon during exhalation is affected mainly by Rsys, ie, the resistance to the displacement of the volume of air loading the balloon. When the balloon valve cannot recoil fast enough (excessive Rsys) at the beginning of exhalation, the exit area for gas efflux is small and increases resistance to flow. We suspect that this might be the case with the MA-2, BEAR-2, and 7200 ventilators because all have an inflatable balloon pressurized by a venturi that tends to apply constant pressure to the balloon, hence constant force. Presumably, the force applied by the balloon may not decrease quickly enough at the onset of exhalation because the loading volume cannot be quickly displaced from the balloon due to the constant force exerted by the venturi and the flow resistance of the narrow venturi throat (ie, high Rsys). Thus, although in theory the inflatable balloon valves on these ventilators are sometimes referred to as “threshold resistors,” they seem to function more as flow resistors (Table 1 and Fig 5). It is notable that the peak expiratory pressure generated may be independent of the CPAP setting during a cough. For example, the 7200 was associated with basically equivalent peak pressure, regardless of the CPAP setting, at peak exhaled flow rates at 200 L/min (Table 1).

The IMV Bird system, by which a pressurized exhalation valve also provides expiratory positive pressure, demonstrated markedly smaller deviations in pressure above the set levels of CPAP at the various exhaled flow rates, as compared with the inflatable-balloon valves. This may be because of low Rsys. With the Bird system the loading volume to the exhalation valve may be readily displaced at the onset of exhalation into a large-volume nebulizer bowl and the ventilator circuit tubing. A rapid “unloading” of the exhalation valve most likely occurs and results in a larger exit area and, thus, lower resistance to exhaled flow. Similarly, the force applied by the Emerson water-column and Boehringer weighted-ball valves may be readily displaced upwards away from the exhalation orifice. There is no constant flow or system pressure to keep these valves from opening as there is with the venturi, which applies constant force to the balloon valves.

Valve resistance and flow rate significantly affect expiratory positive pressure. Thus, the equations for the operation of threshold and flow resistors should be revised to include these additional factors. (See appendix, equations 3 and 4).

We contend that only threshold-resistor, and not flow-resistor, expiratory pressure valves should be used for CPAP and PEEP. Additionally, the threshold resistor should be the low-flow-resistant type because this type of valve may lessen the incidence of barotrauma and other deleterious effects related to airway pressure.

Appendix

The equation of motion for a rectilinear mechanical
system provides a mathematical description of the mode of operation of a "passive" threshold resistor:

$$F = KV + cv + ma$$  \hspace{1cm} (1)$$

where \( F \) is the force applied against the expiratory valve face (in newtons), \( K \) is the elastic modulus (spring constant) of the valve system (in newtons per centimeter), \( I \) is the distance of compression or extension of the valve face from its natural resting position (in centimeters), \( c \) is the viscous resistance opposing valvular movement (in newtons per centimeter per second), \( v \) is the rate of valvular displacement (velocity, in centimeters per second), \( m \) is the inertia (mass, in kilograms) distributed among the moving parts of the valve system, and \( a \) is the system's acceleration (in meters per second squared). \( F \) represents the force exerted by physiologic airway pressure on the valve obstructing the exhalation outlet. This force tends to set the system into motion, ie, opens the valve and allows exhalation. The terms on the right side of the equation oppose motion of the system, ie, keep the valve closed.

The obstructing force applied by an inflatable-balloon threshold-resistor-like device can be expressed as:

$$F = SA (\frac{V}{C} + Rsys \frac{V}{I} + I^2)k$$ \hspace{1cm} (2)$$

where \( SA \) is that part of the internal surface area of the balloon that develops a force in a direction parallel to the exhalation outlet axis in square cm, \( C \) is the compliance of the valve system (in liters per centimeter of water), \( V \) is the displacement volume (proportional to the distance of movement of the valve face) for the opening and closing of the valve (in liters), \( Rsys \) is the system resistance of the balloon to "partial unloading" and "reloading" at the beginning and end of exhalation, respectively (in centimeters of water per liter per second), \( I \) is the rate of volume displacement (flow rate into and out of the balloon, in liters per second), \( m \) is the system inertia (in centimeters of water per liter per second squared) distributed among the wall of the valve and the fluid in motion contained within the balloon, and \( V \) is the volume acceleration (in liters per second squared). The conversion constant, \( k = 9.81 \times 10^{-3} \), is included so that \( F \) is in newtons.

We suggest this revised equation governing the operation of a threshold resistor:

$$\text{expiratory pressure} = \frac{F}{SA} + R (Vexh + Vsys)$$ \hspace{1cm} (3)$$

where \( Vexh \) is the physiologic exhaled flow rate (in liters per sec) and \( Vsys \) is the set flow rate (in liters per sec) directed through the CPAP system. For example, consider a threshold resistor set to generate 10 cm H_2O of expiratory positive pressure with an instantaneous R of 10 cm H_2O/L/sec. Given a \( Vexh \) and \( Vsysis \) of 0.5 L/sec each, then the total expiratory pressure would be 20 cm H_2O, ie, 20 cm H_2O = (0.96 newtons/0.00096 sq m)** +10 cm H_2O/L/sec (0.5 L/sec +0.5 L/sec). A more comprehensive statement describing the operation of a flow resistor can be stated as:

$$\text{expiratory pressure} = R (Vexh + Vsys)$$ \hspace{1cm} (4)$$

In this case, too, \( R \) is the instantaneous resistance.

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**REFERENCES**