Measuring Exhaled Volume with Continuous Positive Airway Pressure and Intermittent Mandatory Ventilation

Techniques and Rationale

Barry J. Weled, M.D.; Don Winfrey; and John B. Downs, M.D., F.C.C.P.

When patients breathe spontaneously through a ventilator circuit, a fall in airway pressure during the inspiratory cycle may increase inspiratory effort. A system of delivery which incorporates a distensible reservoir bag and delivers a constant flow of gas that is two or three times the patient's minute volume will prevent a significant drop in inspiratory airway pressure. Unfortunately, the constant flow of gas mixes with the patient's exhaled gas and makes continuous monitoring of exhaled volumes difficult. Two modifications of circuits are described which allow accurate continuous measurement of volume. One of these circuits allows analysis of the concentrations of expired gases. When spontaneous ventilation occurs, tidal volume and minute ventilation demonstrate an intact connection between the ventilator and the patient, continuously indicate the patient's ability to sustain independent ventilation, and give early warning of a change in respiratory status.

Patients who have arterial hypoxemia, decreased functional residual capacity (FRC), and increased pulmonary venous admixture may benefit from positive end-expiratory pressure (PEEP), which increases FRC and may decrease pulmonary venous admixture. Controlled mechanical ventilation, with or without PEEP, may increase intrapleural pressure enough to impede venous return and reduce cardiac output. It has been suggested that detrimental cardiovascular effects of PEEP may be minimized with intermittent mandatory ventilation (IMV), a means of mechanical ventilatory support that allows unassisted, unrestricted spontaneous respiration between mechanically mediated breaths. Spontaneous respiration lowers the mean intrapleural pressure, which, in turn, may increase cardiac filling and cardiac output.

Spontaneous ventilation with expiratory positive airway pressure (EPAP) but ambient inspiratory airway pressure demands an increased effort to inspire and breathe. This is because of the change in intrapleural pressure which must be generated to drop airway pressure (Paw) from that of expiration to slightly below ambient, in order to draw gas into the lungs. Particularly with high EPAP, subcostal retraction, anxiety, and poor tolerance by the patient of the increased inspiratory effort are common; however, an inspiratory positive airway pressure (IPAP) equal to EPAP can be accomplished with a system of pressurized gas delivery and will lessen the work of breathing more than a spontaneous breathing circuit using EPAP alone. This system incorporates the characteristics of pressure and volume that are found in a flexible anesthesia bag, which generates a gas flow rate sufficient to match the peak inspiratory flow rate of the patient. Systems with only EPAP do not match the peak inspiratory flow rates of most adult patients without a significant decrease in Paw. Other systems have been devised in an attempt to provide IPAP pressure with a noncontinuous demand flow. The peak flow delivery of such systems often is limited by the maximum flow rate of the hospital's sources of compressed oxygen and air and may not be sufficient to meet the patient's peak inspiratory flow demand. Many such systems also lack enough sensitivity to the patient's inspiratory effort to prevent a transient drop in Paw. Although the fall in Paw is less with demand than with EPAP systems, the inspiratory effort is greater than with continuous-flow systems.

Several IMV-PEEP systems have been described for use with mechanical ventilators that have the capability to provide positive EPAP. A few of these ventilators have been equipped to permit ac-
Figure 1. "H" circuit. Inspiratory line of circuit routes gas from air-oxygen blender into anesthesia-bag (2 to 5 L) reservoir (A), one-way valve, heated humidifier (B), and, finally, second one-way valve to patient. Mechanical ventilator is inserted into circuit distal to first one-way valve and anesthesia bag, but proximal to humidifier. During exhalation, continuous gas flow from inspiratory line is diverted to expiratory line by means of bypass, or "H" (C). During spontaneous inspiration, slight drop in Paw allows gas to flow through inspiratory line's one-way valves toward patient. During exhalation, gas must pass through flow transducer (D) and one-way valve in expiratory line of circuit. Exhaled gas mixes with uninhaled gas diverted through bypass, and both exit from circuit through threshold-resistor PEEP valve (E). During mechanically mediated breath, exhalation valve (F) closes, and gas is forced through inspiratory line's second one-way valve and into patient's lung. Charging line of ventilator's exhalation valve may be connected either to standard exhalation valve provided with most disposable ventilator circuits (F) or to top of threshold-resistor exhalation PEEP valve (E). If disposable circuit's exhalation valve is used, it must be distal to bypass tube.

Accurate monitoring of the volume of expired gas during controlled or assisted ventilation. Unfortunately, when ventilators are modified for continuous-flow IMV, these monitors are inaccurate because, although the continuous flow of gas does decrease inspiratory effort, it also contaminates the patient's exhaled gas. Therefore, accurate measurements of minute ventilation and tidal volume are difficult, if not impossible. In addition, calculations for oxygen consumption, production of carbon dioxide, dead space, and the ratio of physiologic dead space over tidal volume \((V_d/V_t)\) are inaccurate when exhaled gases are contaminated; however, we designed two IMV-PEEP circuits which allow accurate measurement of exhaled gas and also maintain IPAP to reduce the effort to breathe.

Figure 2. "H" circuit in greater detail. T-connectors (A) and connector cups (B and D) are commercially available. One-way valves (C) should be type that will not be disrupted by water condensation. Flow-volume sensors (E) are commercially available (Foregger electronic spirometer 510 and Monaghan ventilation monitor 700). "H" valve system may be adapted to fit commercially available disposable ventilator circuit manifolds.
DESCRIPTION OF SYSTEM

To prevent a significant drop in inspiratory Paw, we put a 5-L anesthesia bag in conjunction with a source of continuous gas flow in the inspiratory line of the ventilator's breathing circuit (Figs 1 to 3). The characteristics of compliance of the anesthesia bag prevent a significant reduction in Paw as long as the rate of continuous gas flow exceeds the patient's minute ventilation. Figures 1 and 2 illustrate a modified system for constant flow delivery which allows accurate measurement of VT and minute ventilation. With this modification, a continuous flow of gas passes through an anesthesia bag and a heated humidifier in the inspiratory line. During exhalation, the continuous gas flow enters a bypass tube and is directed through a threshold-resistance PEEP valve. Gas cannot flow back toward the patient because of a one-way valve in the expiratory line. During spontaneous inhalation, a one-way valve in the inspiratory line opens, and gas flows to the patient. The patient's exhaled gas passes through a flow transducer, and gas flows to the patient. The patient's exhaled gas passes through a flow transducer and an exhalation valve. Thereafter, it mixes with the continuous gas flow diverted from the inspiratory line and then passes through an exhalation valve and a threshold-resistance PEEP valve. This modification works well with a simple system for CPAP or a CPAP-IMV circuit (Fig 1). Although accurate measurement of the volume of exhaled gas can be obtained, the collection and analysis of gases is not possible because of contamination from the continuous gas flow.

In order to collect uncontaminated gas, we devised another system which diverts the uninhaled continuous gas flow from the inspiratory line but does not allow it to mix with exhaled gas. Continuous gas flow enters a bypass tube and is directed through an additional threshold resistor in the inspiratory line. During a mechanically mediated breath, gas flows past the bypass tube through a low-resistance one-way valve to the patient. Both threshold-resistor valves must be charged closed by the ventilator during a mechanically mediated breath. In addition, the threshold-resistor valve in the inspiratory line must be charged to a pressure approximately 1 cm H2O less than that applied to the PEEP valve in the expiratory line. During spontaneous inspiration, pressure falls on the patient's side of the one-way valve in the inspiratory line, opens the one-way valve, and allows gas to flow to the patient. At the end of inspiration, the resistance to the flow of gas increases. The inspiratory one-way valve closes, and gas is again diverted away from the patient and passes through the inspiratory threshold-resistant valve to the atmosphere. The one-way valve in the inspiratory line prevents exhaled gas from entering the inspiratory circuit. As the patient exhales, the Paw will increase and force exhaled gas through a flow transducer and a threshold-resistor PEEP-exhalation valve. This system can create a positive Paw during both inhalation and exhalation. Expiratory Paw is determined by the resistance set at the PEEP valve on the expiratory line. In contrast, the inspiratory Paw, which must always be slightly less than that of the expiratory Paw, can be determined by the pressure set at the inspiratory threshold resistor as long as the constant flow rate exceeds the patient's minute volume. This system allows uncontaminated exhaled gas to be collected from the exhalation-PEEP valve. Thus, analysis of the concentrations of oxygen and carbon dioxide and the exhaled volume can be readily obtained.

Certain criteria for the choice of one-way valves in these systems must be strictly enforced. These include the following: (1) low flow resistance; (2) direction of one-way flow must be clearly marked on the valve; and (3) visibility of the valvular motion while in use. We have used these circuits for two years, and they have functioned well, except for one.

Figure 3. Double PEEP-valve system. Gas from mechanical ventilator and from continuous-flow source (A) must pass through one-way valve and heated humidifier (B). During exhalation, continuous gas flow takes path of least resistance and is diverted through threshold-resistor valve (C), which is pressurized to 1 cm H2O less than threshold-resistor valve (D) in expiratory line. During spontaneous inspiration, gas flows to patient through second one-way valve in inspiratory line. Exhaled gas is directed through threshold-resistor exhalation-PEEP valve (D) and flow transducer (E). During mechanically mediated breath, ventilator exhalation charging line causes both threshold-resistor valves to close and force gas to patient through inspiratory line.
instance when a one-way valve was placed backwards in the circuit.

**DISCUSSION**

Continuous monitoring of minute ventilation and $V_t$ with the IMV and continuous-flow CPAP circuits provides several advantages not possible with widely used disconnect (or apnea) alarms. During controlled mechanical ventilation and, to a lesser extent, during assisted mechanical ventilation, $V_t$ and minute ventilation are determined by the ventilator’s settings; however, when IMV is used, minute ventilation and spontaneous $V_t$ are determined by the patient; and, therefore, measurement of spontaneous $V_t$ and minute ventilation not only ensures an intact circuit between patient and ventilator but also allows the clinician to continuously assess a patient’s ability to sustain independent ventilation. Therefore, when spontaneous ventilation is allowed, $V_t$ is a reflection of the patient’s ventilatory status, rather than a measurement of the mechanically delivered breath reaching the patient’s lungs. For example, subjects with either normal or diseased lungs will adjust their respiratory rate and $V_t$ to minimize the work of breathing. The elastic resistance of the lung, which is quantified by pulmonary compliance, increases with increasing $V_t$. In order to minimize the effort to breathe, patients with stiff lungs may have decreased $V_t$. Because anatomic dead space is relatively constant, the respiratory rate and total minute ventilation must increase to maintain alveolar minute ventilation. The empiric evidence fits the following equation: $W_{el} = \frac{3}{2} V_t/C$, where $W_{el}$ is the inspiratory work necessary to overcome elastic resistance for one breath, and $C$ is compliance.

We have seen patients who developed the adult respiratory distress syndrome after surgery in whom the “high” minute ventilation alarm threshold gave the first clinical indication of a change in respiratory status. A “low” minute ventilation alarm also gives early warning of a deteriorating respiratory condition. A sufficiently decreased pulmonary compliance may compromise the patient’s ability to maintain adequate minute ventilation and, thus, trigger a low threshold alarm. Such information could not be obtained during controlled or assisted mechanical ventilation. In addition, patients with low rates of IMV who hypoventilate because of excessive doses of narcotics or other sedatives are also protected with the “low” minute ventilation alarm.

Frequent monitoring of $V_t$ in a continuous-flow circuit is important even with constant-volume ventilators. Recently, a continuous flow of gas into the spontaneous breathing circuit of an IMV ventilator was shown to greatly increase the volume of the mechanical breath. The magnitude of the $V_t$ generated by the ventilator depends on its inspiratory flow setting and the continuous flow rate of gas into the circuit. Low settings for the ventilator’s peak flow rate and high settings for the continuous flow rate tend to increase the mechanical $V_t$ as much as 300 percent of that determined by the ventilator’s setting.

We believe that it is desirable to measure the spontaneous $V_t$ often and the total minute ventilation continuously in patients receiving IMV. Total minute ventilation is a measure of the volume delivered by the ventilator plus the volume inhaled spontaneously by the patient. These measurements give early warning of deteriorating pulmonary function and serve as a reserve alarm to standard apnea alarms on ventilators. In order to minimize the effort to breathe, an IPAP also is desirable. We have described two methods with continuous-flow IMV circuits which allow measurement of exhaled $V_t$ and total minute ventilation. These circuits are safe, inexpensive, and easily assembled.

**REFERENCES**