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Demand Valve Improperly Set Resulting in Pulmonary Barotrauma

MICHAEL J. BANNER, R.R.T.,* AND PHILIP G. BOYSEN, M.D.†

Demand valves are incorporated into intermittent mandatory ventilation (IMV) and continuous positive airway pressure (CPAP) systems to provide intermittent, high flow during spontaneous inhalation. The high flow serves to reduce spontaneous inspiratory work and maintain high inspiratory positive airway pressure during CPAP.[1]

A correctly set demand valve should provide an intermittent and not a continuous rate of flow in an IMV–CPAP system, *i.e.*, only during spontaneous inhalation should gas flow from the demand valve. However, if the demand valve is set improperly, flow will be continuous. During mechanical inhalation (IMV), the continuous flow from the demand valve may augment the ventilator tidal volume (V_T).[2]

We report on a consequence of an improperly set demand valve used in an IMV–CPAP system that can be hazardous to patients.

REPORT OF A CASE

The trachea of a 73-kg adult with a diagnosis of acute respiratory failure secondary to infection was intubated and the tube was attached to an Emerson 3-PV IMV ventilator incorporating an adjustable demand valve. Mechanical V_T was set at 950 ml and IMV at 6 breaths·min^{-1} with CPAP of 15 cmH$_2$O. The inspiratory time was set at approximately 2 s. The peak inflation pressure (PIP) during IMV was approximately 45 cmH$_2$O. Effective compliance was calculated at 0.03 l·cmH$_2$O^{-1}. The reference pressure control of the demand valve was adjusted so that flow was intermittent and occurred only when the patient initiated a spontaneous breath. During spontaneous inhalation, airway pressure decreased from 15 to 11 cmH$_2$O, which indicated that flow from the demand valve was adequate to maintain CPAP.

Later in the day the patient became tachypneic (spontaneous breathing increased from 15 to 40 breaths·min^{-1}) and, during spontaneous inhalation, airway pressure decreased from 15 to 4 cmH$_2$O. The reference pressure control of the demand valve was then set at maximum, which produced a continuous rate of flow high enough to raise airway pressure from 4 to 12 cmH$_2$O during spontaneous inhalation. Then during IMV the PIP suddenly increased to 80 cmH$_2$O. Subsequently, the patient became hypotensive (65/40 mmHg) and a pneumothorax resulted.

The patient was disconnected from the ventilator and ventilated with a self-inflating bag, and a chest tube was inserted immediately. Lung expansion later was confirmed by roentgenographic examination. Subsequently, ventilation was provided by another ventilator; the patient recovered uneventfully.

METHODS

To duplicate this complication, we attached an Emerson 3-PV IMV ventilator with a demand valve CPAP system to a test lung (Michigan Instruments, Inc.). The test lung was set at a compliance of 0.03 l·cmH$_2$O^{-1} and at normal airway resistance. A pneumotachograph attached to a differential pressure transducer and a separate airway pressure transducer were connected to an amplifier–integrator–recorder system to measure real-time waveforms of airway flow, V_T, and PIP during mechanical ventilation. All measurements were made at the connection between the endotracheal tube and the ventilator circuit.

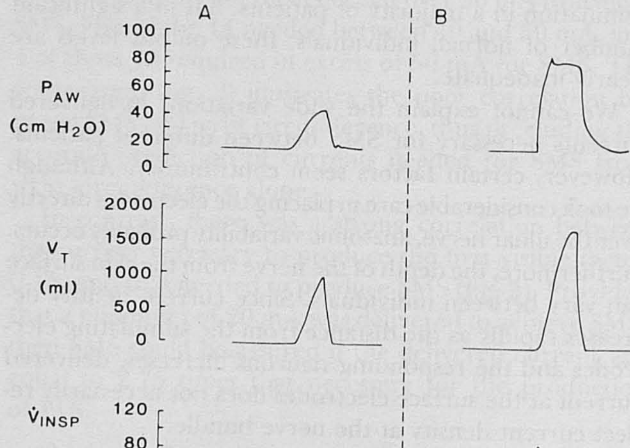

FIG. 1. *A.* Airway pressure (P_{AW}), tidal volume (V_T), and inspiratory flowrate ($\dot{V}_{INSP}$) were measured with the ventilator attached to a test lung. The test lung was set to mimic the patient's effective compliance (0.03 l/cm H$_2$O). Ventilator V_T and inspiratory time (flow rate) controls were set at 950 ml and 2 s, respectively. The demand valve was set and used in combination with a water-weighted expiratory pressure valve (threshold resistor) to maintain a continuous positive airway pressure of 15 cmH$_2$O. (These were the same settings as previously applied to the patient.) *B.* The reference pressure control of the demand valve was set improperly at the maximum position, which resulted in a continuous rate of flow (all other ventilator settings remained constant).

* Assistant in Anesthesiology.

† Associate Professor of Anesthesiology and Internal Medicine.

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Address correspondence and reprint requests to Dr. Boysen, Department of Anesthesiology, Box J-254, J.H.M.H.C., Gainesville, Florida 32610.

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The ventilator was adjusted to the exact settings used for the patient, *i.e.*, V_T 950 ml, CPAP 15 cmH_2O, and mechanical inspiratory time 2 s, and airway flow, V_T, and PIP were measured. The reference pressure control on the demand valve then was set at maximum while keeping all other ventilator settings constant and measurements were repeated.

RESULTS

When the demand valve was set properly, the peak flow rate generated by the ventilator during mechanical inhalation was 56 $l \cdot min^{-1}$; total peak flow rate measured during mechanical inhalation when the demand valve was improperly set was 82 $l \cdot min^{-1}$. Under the latter condition, V_T and PIP increased to 1700 ml and 84 cmH_2O, respectively (compare figs. 1*A* and *B*).

DISCUSSION

Spontaneous inhalation with a demand valve IMV-CPAP system (as in the Emerson ventilator) is possible when a one-way valve separates the mechanical ventilator and a demand valve opens to permit flow to the patient. When CPAP is used, the spontaneous inspiratory effort required to open the one-way, and demand valves, ideally, should be minimal, *i.e.*, the reference pressure setting of the demand valve should be the same as the expiratory pressure level during CPAP. Thus, the pressure differential across the one-way valve is negligible before inhalation. At the beginning of spontaneous inhalation, as airway pressure decreases, the pressure on the patient's side of the one-way valve decreases, which causes it and the demand valve to open immediately. The demand valve then should accelerate flow sufficiently to meet the patient's requirements for inspiratory flow and to maintain positive airway pressure. During exhalation, airway pressure increases. At end-exhalation there is no pressure gradient across the one-way valve and, thus, flow from the demand valve is terminated.

However, in this case, when the demand valve was set improperly by adjusting the spring tension control on the reference pressure chamber to maximum, the pressure gradient across the one-way valve was continuous during all phases of spontaneous breathing. Under this condition, the reference pressure set in the demand valve was greater than the CPAP level and resulted in continuous flow through the open one-way valve and into the CPAP/ventilator circuit. During the IMV breath, continuous flow from the demand valve was added to the flow from the ventilator and potentiated the preset V_T (fig. 2).

A safety factor that could be used is real-time or continuous measurements of V_T. With this patient, if V_T had been displayed in real-time it would have indicated that abnormally large volumes suddenly were being administered that necessitated immediate evaluation and

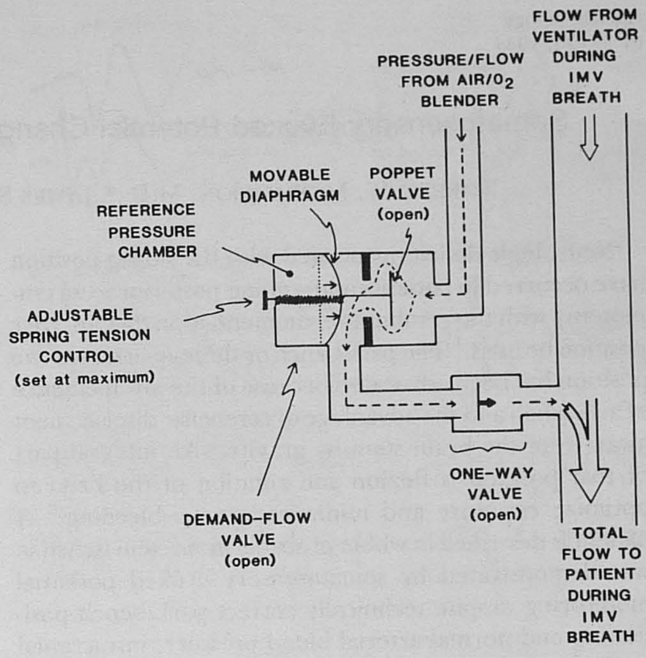

FIG. 2. Spring tension control on demand valve reference pressure chamber is set improperly to maximum tension; this forces the movable diaphragm and poppet valve to the right (open) and allows continuous flow through the open one-way valve and then into the inspiratory limb of the ventilator circuit. When the intermittent mandatory ventilation (IMV) breath is delivered to the patient, flow from the ventilator combines with continuous flow from the demand valve, which results in excessive IMV tidal volume and peak inflation pressure.

intervention.[3,4] Real-time and not intermittent measurements of V_T, airway flow, and pressure would have been useful for monitoring the ventilation of this patient.

In the event that a demand valve does not deliver enough flow to satisfy a patient's spontaneous, inspiratory flow demand, a reservoir bag may compensate for inadequate flow delivery. A 5-l reservoir bag connected to a Y-piece and attached to the demand valve outflow port may be used as a reservoir for additional flow.

Finally, in our experience, the Emerson demand valve has been an effective and reliable device. Operator error, not equipment malfunction, resulted in the complication just described.

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