Basic Pulmonary Mechanics during Mechanical Ventilation

Assessment of Mechanics during Mechanical Ventilation
- Airway Pressure
- Auto-PEEP
- Mean Airway Pressure
- Compliance
- Resistance
- Work of Breathing

Assessment of Spontaneous Breathing
- Rate and Tidal Volume
- Maximal Inspiratory Pressure
- Vital Capacity

Pulmonary mechanics are frequently measured on mechanically ventilated patients. Some, such as peak inspiratory pressure (PIP), are recorded as part of patient-ventilator system checks. Others can easily be made at the bedside with no equipment but that available on the ventilator (e.g., airway pressure, flow, and volume). When lung mechanics are measured with mechanically ventilated patients, the site of measurement is important. Pressure, flow, and volume should ideally be measured at the proximal airway. Commercially available mechanical ventilators monitor pressure and flow at a variety of sites, which may affect the measured values obtained.

Assessment of Mechanics during Mechanical Ventilation

Airway Pressure
A typical airway pressure waveform during volume ventilation is shown in Fig. 26-1. With volume ventilation, pressure increases during inspiration as volume is delivered. The slope of the pressure curve depends upon the inspiratory flow pattern. If a constant flow pattern is chosen, there will be a linear increase in pressure during inspiration. With a decelerating flow pattern, the inspiratory pressure waveform will be convex. The peak inspiratory pressure varies directly with resistance, end-inspira-
tory flow, tidal volume, PEEP, and elastance (i.e., inversely with compliance). Depending upon the inspiratory flow waveform, PIP may not occur at end-inspiration.

An end-inspiratory pause of sufficient duration (0.5 to 2.0 s) will allow equilibration between proximal airway pressure and alveolar pressure (Palv). This measurement should be made on a single breath and removed immediately to prevent development of auto-PEEP. During the end-inspiratory pause, there is no flow, and a pressure plateau develops as proximal airway pressure equilibrates with Palv. The pressure during the inspiratory pause is commonly referred to as plateau pressure and represents peak Palv. The difference between PIP and peak Palv is due to the resistive properties of the system (e.g., pulmonary airways, artificial airway), and the difference between peak Palv and total PEEP is due to the elastic properties of the system (i.e., lung and chest wall compliance).

During pressure ventilation, PIP and peak Palv may be equal (Chap. 4). This is due to the flow waveform that occurs during this mode of ventilation. With pressure ventilation, flow decreases during inspiration and is often followed by a period of zero flow at end-inspiration. During this period of no flow, proximal airway pressure should be equal to peak alveolar pressure. During pressure support ventilation, the pressure support level is the maximal peak Palv but will not represent transpulmonary pressure if the patient is actively inhaling.

From the above discussion, it follows that PIP should be lower during pressure ventilation than during volume ventilation. With volume ventilation, PIP will be greater than peak Palv due to the presence of end-inspiratory flow. With pressure ventilation, PIP will equal peak Palv if end-inspiratory flow is zero. With all other factors held constant (e.g., tidal volume, lung impedance, PEEP), peak Palv is identical for volume and pressure ventilation. Because lung injury is related primarily to peak Palv (i.e., plateau pressure), the importance of the decrease in PIP that occurs in changing from volume to pressure ventilation is questionable.

AUTO-PEEP

An end-expiratory pause can be used to determine auto-PEEP (Fig. 26-1). This method is valid only if the patient is not breathing spontaneously and there are not system leaks (e.g., circuit leak or bronchopleural fistula). For patients who are assisting or breathing spontaneously, an esophageal balloon is needed to determine auto-PEEP (Chap. 27). During the end-expiratory pause, there is an equilibration between end-expiratory pressure (total PEEP, PEEPtot) and proximal airway pressure. The difference between set PEEP and PEEPtot is auto-PEEP. An end-expiratory pause can be applied on some ventilators by use of the expiratory hold control. For ventilators that do not have this control, auto-PEEP can be measured by use of a Braschi valve (Fig. 26-2). It is difficult to detect auto-PEEP unless it is specifically measured, since it varies directly with tidal volume, compliance, and resistance and inversely with expiratory time. This is illustrated by the relationship

\[
\text{auto-PEEP} = V_T \div \left[ (C) \cdot \left( e^{K_E \cdot T_e} \right) \right]
\]

where \( K_E = 1/(R_e \cdot C) \), \( e \) is the base of the natural logarithm, and \( T_e \) is expiratory time. It is important to detect the presence of auto-PEEP because it can cause hyperinflation, barotrauma, and hemodynamic instability. Auto-PEEP will also make triggering
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**Figure 26-2** Use of a Braschi valve to measure auto-PEEP. With the Braschi valve closed (A), the ventilator works normally. With the Braschi valve opened during expiration (B), an end-expiratory pause equal in duration to the inspiratory time is created.

more difficult with assisted and spontaneous breathing.

**MEAN AIRWAY PRESSURE**

Many of the desired and deleterious effects of mechanical ventilation are determined by mean airway pressure ($\bar{P}_{aw}$) (Chap. 1). Factors affecting mean airway pressure are PIP, PEEP, I:E ratio, respiratory rate, and the inspiratory pressure waveform. During pressure ventilation, the inspiratory pressure waveform is rectangular and $\bar{P}_{aw}$ is estimated as

$$\bar{P}_{aw} = (\text{PIP} - \text{PEEP}) \cdot (T_{i}/T_{r}) + \text{PEEP}$$

For example, with a PIP of 40 cmH₂O, PEEP of 10 cmH₂O, Ti of 1 s, rate 15/min (Tᵢ/Tᵣ = 0.33), $\bar{P}_{aw}$ is 20 cmH₂O. During constant-flow volume ventilation, the inspiratory pressure waveform is triangular and $\bar{P}_{aw}$ can be estimated as

$$\bar{P}_{aw} = (0.5) \cdot (\text{PIP} - \text{PEEP}) \cdot (T_{i}/T_{r}) + \text{PEEP}$$

For example, with a PIP of 25 cmH₂O, PEEP 5 cmH₂O, Ti 1.5 s, rate 20/min (Tᵢ/Tᵣ = 0.5), $\bar{P}_{aw}$ is 10 cmH₂O. Many current-generation microprocessor ventilators display $\bar{P}_{aw}$ from integration of the airway pressure waveform. Typical $\bar{P}_{aw}$ values for passively ventilated patients are 5 to 10 cmH₂O (normal), 15 to 30 cmH₂O (ARDS), and 10 to 20 cmH₂O (airflow obstruction).

Because there is often an imbalance between inspiratory and expiratory resistances, mean airway pressure is not equivalent to mean alveolar pressure. The difference between mean alveolar pressure ($\bar{P}_{alv}$) and $\bar{P}_{aw}$ is estimated by the following relationship:

$$\bar{P}_{alv} - \bar{P}_{aw} = (\bar{V}_{E} + 60) \cdot (R_{t} - R_{i})$$

where $R_{i}$ is inspiratory airways resistance.

**COMPLIANCE**

The difference between Pplat and PEEPtot is determined by the combined compliance of the lung and chest wall. Thus, compliance can be calculated as

$$C = V_{T} \div (\text{Pplat} - \text{PEEPtot})$$

where Pplat is end-inspiratory plateau pressure. The $V_{T}$ used in this equation is the actual tidal volume delivered to the patient and should be corrected for
Table 26-1 Causes of Decreased Compliance and Increased Resistance in Mechanically Ventilated Patients

<table>
<thead>
<tr>
<th>Compliance</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pneumothorax</td>
<td>Bronchospasm</td>
</tr>
<tr>
<td>Mainstem intubation</td>
<td>Secretions</td>
</tr>
<tr>
<td>Congestive heart failure</td>
<td>Small endotracheal tube</td>
</tr>
<tr>
<td>ARDS</td>
<td>Mucosal edema</td>
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<tr>
<td>Consolidation</td>
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<tr>
<td>Pneumonecctiony</td>
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<tr>
<td>Pleural effusion</td>
<td></td>
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<tr>
<td>Abdominal distension</td>
<td></td>
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<tr>
<td>Chest wall deformity</td>
<td></td>
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</tbody>
</table>

the effects of volume compressed in the ventilator circuit. The PEEПtot should include any auto-PEEP that is present. The Pplat should be determined from an end-inspiratory breath-hold that is long enough to produce equilibration between proximal airway pressure and alveolar pressure. Causes of a decrease in compliance in mechanically ventilated patients are listed in Table 26-1.

RESISTANCE

The difference between PIP and Pplat is determined by inspiratory resistance and end-inspiratory flow. During constant-flow volume ventilation, inspiratory resistance can be calculated as

$$R_I = (\text{PIP} - \text{Pplat}) / \dot{V_I}$$

where $\dot{V_I}$ is the inspiratory flow. Expiratory resistance can also be estimated as

$$R_E = (\text{Pplat} - \text{PEEPtot}) / \dot{V_{E\text{max}}​}$$

where $\dot{V_{E\text{max​}}​}$ is the peak expiratory flow. Causes of increased resistance during mechanical ventilation are listed in Table 26-1. Inspiratory resistance is typically less than expiratory resistance because of the increased diameter of airways during inspiration and the presence of the endotracheal tube.

WORK OF BREATHING

Inspiratory work of breathing performed by the ventilator can be estimated during constant-flow passive inflation of the lungs by the following calculation:

$$W = (\text{PIP} - (0.5 \cdot \text{Pplat}) / 100) \cdot V_T$$

For example, if PIP = 35 cmH\text{ }_2\text{ }O, Pplat = 30 cmH\text{ }_2\text{ }O, and tidal volume = 0.6 L, then $W = 0.12$ kg·m, or 0.2 kg·m/L. Note that the units for work of breathing are kilogram-meter (kg·m) or joules (J); 0.1 kg·m = 1.0 J. Normal work of breathing is 0.5 J/L. Work of breathing will increase with an increase in resistance, a decrease in compliance, or an increase in tidal volume. Work of breathing is often normalized to the tidal volume (work/L). Although work of breathing is not commonly calculated, it is reasonable to expect that patients with a high work of breathing will not be weaned from mechanical ventilation.

ASSESSMENT OF SPONTANEOUS BREATHING

RATE AND TIDAL VOLUME

Assessment of spontaneous respiratory rate and tidal volume is useful, particularly in patients being weaned from mechanical ventilation. Tachypnea is an ominous sign and may be either a symptom or cause of respiratory muscle fatigue. Development of a pattern of rapid and shallow breathing during a weaning trial usually predicts failure. A rate:tidal volume ratio greater than 100 predicts a failed weaning trial. For example, a patient with a spontaneous rate of 30/min with a tidal volume of 0.2 L (ratio = 150) will probably not be weaned from mechanical ventilation. On the other hand, a patient with a spontaneous rate of 20/min and a tidal volume of 0.25 L (ratio = 80) is more likely to be weaned successfully.

In assessing respiratory rate, it should be counted
for an entire minute. Tidal volume can be measured using portable hand-held devices such as the Wright respirometer. In measuring tidal volume, a one-way valve system should be used to isolate the patient from the spirometer. Rebreathing through the spirometer could be a source of nosocomial infection. The exhaled volume should be collected for 1 min (minute ventilation) and the respiratory rate counted for that minute. Tidal volume is then calculated by dividing the minute ventilation by respiratory rate.

MAXIMAL INSPIRATORY PRESSURE

The maximal inspiratory pressure (MIP) is measured by attaching a manometer to the endotracheal or tracheostomy tube. The patient then forcibly inhales against an occluded airway after maximal exhalation. When MIP is measured, a unidirectional valve should be used and the airway completely obstructed for as long as 20 s (Chap. 10). The patient must be closely monitored and the maneuver terminated if signs of cardiopulmonary distress occur. An MIP more negative than −30 cmH2O usually suggests adequate inspiratory muscle strength.

VITAL CAPACITY

Vital capacity is the maximum volume that can be exhaled following maximal inhalation. Unlike the MIP maneuver, vital capacity requires patient cooperation, which often renders the results unreliable. A reduced vital capacity indicates less respiratory muscle reserve and decreased ability to deep-breathe and cough. Particularly in patients with neuromuscular disease, a reduced vital capacity (<10 mL/kg) indicates the need for intubation and mechanical ventilation (see Chap. 16). Patients with a reduced vital capacity are also less likely to be successfully weaned from mechanical ventilation.

POINTS TO REMEMBER

- During volume ventilation, PIP is determined by tidal volume, inspiratory flow, resistance, compliance, and PEEP.
- Peak alveolar pressure is estimated by measuring proximal airway pressure during an end-inspiratory breath-hold.
- Auto-PEEP is estimated by measuring proximal airway pressure during an end-expiratory breath-hold.
- Mean airway pressure is estimated from PIP, PEEP, and Ti/Tr.
- Compliance is calculated from VT, Pplat, and PEEP.
- Inspiratory resistance is calculated from PIP, Pplat, and inspiratory flow; expiratory resistance is calculated from Pplat and expiratory flow.
- Work of breathing is increased with increases in resistance, compliance, and VT.
- A pattern of rapid shallow breathing predicts a failed weaning trial.
- Maximal inspiratory pressure is an indicator of inspiratory muscle strength.
- Vital capacity is an indicator of respiratory reserve and ability to deep-breathe and cough.

BIBLIOGRAPHY


