CHAPTER 27

Advanced Pulmonary Mechanics
during Mechanical Ventilation

SCALARS
Pressure
Flow
Volume

LOOPS
Flow-Volume Loops
Pressure-Volume Loops

TRACHEAL PRESSURE

ESOPHAGEAL PRESSURE
Patient versus Ventilator Work of Breathing
Auto-PEEP with Spontaneous Breathing
Transmission of Pressure to the Pleural Space

SCALARS
PRESSURE

Much qualitative information can be obtained by observing the airway pressure waveform (Fig. 27-1). With patient-triggered breaths, airway pressure dips below baseline to trigger the ventilator. Active patient work often continues after the initiation of an assisted breath, which produces scalloping of the airway tracing during an assisted breath (Fig. 27-2). This suggests that the inspiratory flow of the ventilator should be increased. The depth and duration of the negative pressure deflection prior to a patient-assisted breath indicates the response of the ventilator, and the depth and duration of the negative pres-
Table 27-1 Influence of the Site of Pressure Measurement and Mode of Ventilation on Measurements of Work of Breathing and Compliance

<table>
<thead>
<tr>
<th>Site of Pressure Measurement and Mode of Ventilation</th>
<th>Area of the Pressure-Volume Loop = Work Done to Overcome</th>
<th>Slope of the Pressure-Volume Loop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Esophageal pressure during spontaneous ventilation</td>
<td>Pulmonary inspiratory and expiratory resistance</td>
<td>Lung compliance</td>
</tr>
<tr>
<td>Esophageal pressure during mechanical ventilation</td>
<td>Chest-wall inspiratory and expiratory resistance</td>
<td>Chest-wall compliance</td>
</tr>
<tr>
<td>Pressure at tracheal (carinal) end of endotracheal tube during spontaneous ventilation</td>
<td>Imposed inspiratory and expiratory resistance of the total breathing apparatus (i.e., endotracheal tube, breathing circuit, and the ventilator)</td>
<td>Compliance of the total breathing apparatus</td>
</tr>
<tr>
<td>Pressure at the tracheal (carinal) end of endotracheal tube during mechanical ventilation</td>
<td>Pulmonary and chest-wall inspiratory and expiratory resistance</td>
<td>Compliance of the respiratory system (lungs plus chest wall)</td>
</tr>
<tr>
<td>Pressure at airway opening (between “Y” piece of breathing circuit and endotracheal tube) during spontaneous ventilation</td>
<td>Imposed inspiratory and expiratory resistance of the breathing circuit and ventilator</td>
<td>Compliance of the breathing circuitry</td>
</tr>
<tr>
<td>Pressure at airway opening during mechanical ventilation</td>
<td>Pulmonary and chest-wall inspiratory and expiratory resistance, plus resistance of the endotracheal tube</td>
<td>Compliance of the respiratory system (lungs plus chest wall)</td>
</tr>
</tbody>
</table>


sure deflection during a spontaneous breath (i.e., during SIMV) indicates the effort required to obtain flow from the ventilator demand valve.

Ventilator systems measure pressure at a number of sites in the system. Proximal airway pressure should be measured directly at the endotracheal tube. Some ventilator systems approximate inspiratory pressure by measuring pressure in the expiratory circuit during inspiration; they approximate expiratory pressure by measuring pressure in the

**Figure 27-1** Airway pressure waveform produced with constant flow and decelerating flow inspiration.

**Figure 27-2** Active inspiration during positive pressure ventilation produces scalloping of the airway pressure waveform.
inspiratory circuit during expiration. Although this should theoretically be satisfactory, it may not allow precise reflections of proximal airway pressure throughout a dynamically changing respiratory cycle. Bedside lung mechanics systems (e.g., Bicore, Ventra) and some ventilators measure pressure directly at the proximal airway.

A typical airway pressure waveform is shown in Fig. 27-1. During expiration, the pressure should be the set PEEP level. During inspiration, the airway pressure waveform is determined by the flow delivery set on the ventilator and the patient’s ventilatory demand. With constant flow ventilation, airway pressure should increase linearly during inspiration. With a decelerating flow pattern, airway pressure during inspiration approximates a square wave. Pressure modes of ventilation (e.g., pressure control, pressure support) should ideally produce a square pressure waveform because of the decelerating flow that occurs with these modes.

FLOW

Flow can be measured at a number of positions in the ventilator system. Ideally, flow should be measured at the proximal airway. Although most ventilator systems do not measure flow at this site, lung mechanics analyzers (e.g., Bicore, Ventra) measure flow by placing a pneumotachometer directly at the proximal endotracheal tube. Flow measured directly at the airway is not affected by factors such as system leaks and the compressible volume of the ventilator circuit.

A typical airway flow waveform is illustrated in Fig. 27-3. With volume modes, the inspiratory waveform is determined by the flow setting of the ventilator; with pressure modes, the inspiratory flow decelerates (Chap. 4). If an end-inspiratory pause is set with volume modes or a long inspiratory time is used with pressure modes, a period of zero flow occurs at the end of the inspiratory phase.

The shape of the expiratory flow waveform is determined by the time constant of the lungs. With a normal time constant (i.e., normal resistance and compliance), expiratory flow quickly rises to a peak and then decreases throughout expiration. Flow should decrease to zero during expiration. Flow at end-expiration indicates that auto-PEEP is present but does not indicate the amount of auto-PEEP. It should also be recognized that auto-PEEP may be present even if expiratory flow is apparently zero at end expiration. Although useful, the end-expiratory flow is thus an insensitive and imprecise indicator of auto-PEEP. We recommend that end-expiratory hold methods be routinely used to detect and quantify auto-PEEP (Chap. 26).

VOLUME

Most monitoring systems used with mechanical ventilators do not measure volume directly. The flow waveform is integrated to produce volume (\( \int V \, dt \)). Because most systems measure flow more accurately in one direction (usually inspiration) than the other, it is not unusual for inspiratory and expiratory volumes to be slightly different. The volume waveform depends upon the flow pattern set on the ventilator (Fig. 27-4). With constant flow, volume delivery is linear during inspiration. With decelerating flow, most of the volume is delivered early in the inspiratory period. A leak distal to the point of volume measurement (e.g., leak around the endotracheal tube, bronchopleural fistula) will produce a gross difference between the volume delivered during inspiration and the volume expired.
PRESSURE-VOLUME LOOPS

Pressure-volume loops are displayed with volume (ordinate) as a function of pressure (abscissa). The area of the pressure-volume loop to the left of the pressure baseline is the work performed by the patient to trigger the ventilator (Fig. 27-7). The slope of the pressure-volume loop is the lung/chest wall compliance (Fig. 27-8); the area to the left of the pressure-volume loop represents inspiratory work done by the ventilator to inflate the lungs (Fig. 27-9). The area inside the dynamic pressure-volume loop represents resistive work and is increased with diseases that increase the resistive work of breathing (Fig. 27-10). A lower inflection point (convexity) of the pressure-volume loop indicates an opening pressure of the lungs (Fig. 27-11), and PEEP should set at or above this inflection point. An upper inflection point (concavity) of the pressure-volume loops (Fig. 27-11) indicates hyperinflation (i.e., the elastic limits of the lungs are exceeded) and the tidal volume should be decreased. Inflection points on the pressure-volume loop can be detected only with constant flow inflation and cannot be determined with decelerating flow waveforms. Correct interpretation of this loop during nonconstant flow ventilation (e.g., pressure ventilation) is unclear. Correct interpretation of pressure-volume and flow-volume loops also assumes that the patient is relaxed and breathing in synchrony with the ventilator. If the patient is actively breathing, esophageal pressure measurements are needed to completely assess lung and chest wall mechanics (see below).

TRACHEAL PRESSURE

The effect of endotracheal tube resistance on proximal airway pressure can be overcome by measuring tracheal pressure. This can be accomplished by passing a narrow-bore catheter to the distal tip of the endotracheal tube, which may allow tracheal pressures to be used to trigger the ventilator. Measurements of tracheal pressure may also be useful to titrate pressure support levels to overcome the imposed work of breathing through the endotracheal tube. Although measurement of tracheal pressure is
attractive, the clinical feasibility of this is currently unclear.

**ESOPHAGEAL PRESSURE**

Esophageal pressure is a reflection of intrapleural pressure, and is used to identify changes in intrapleural pressure during ventilatory maneuvers. In critically ill patients in a supine position, the absolute value for esophageal pressure often overestimates the true intrapleural pressure due to the weight of the mediastinal viscera. However, a properly placed esophageal balloon will accurately reflect changes in pleural pressure regardless of patient position. The esophageal balloon is placed in the lower third of the esophagus (about 35 to 40 cm from the nares in most adults). The balloon is filled and then all but 0.5 to 1.0 mL is removed.

In the spontaneously breathing subject, proper placement can be evaluated using the Baydur maneuver, in which airway and esophageal pressures are evaluated during airway occlusion. If the balloon is properly placed, equal changes will be noted for esophageal and airway pressure changes during airway occlusion. Proper position of the esophageal balloon can also be assessed by the observation of cardiac oscillations on the esophageal pressure waveform. In critically ill patients, esophageal pressure is most commonly monitored by use of an esophageal balloon on a gastric tube. This allows esophageal pressure measurements concurrent with
Figure 27-6 Changes in flow-volume (left) and pressure-volume (right) loops that occur with bronchodilation. Also indicated is the airway resistance (R) before and after bronchodilation. Note the increased expiratory flow after bronchodilation (resistance decrease from 26 cmH₂O/L/s to 21 cmH₂O/L/s). Also note the decrease in area within the pressure-volume loop after bronchodilation.

Figure 27-7 Pressure-volume loop illustrating work performed to trigger the ventilator. The area of the loop to the left of baseline pressure represents trigger work.

feedings or gastric suction. In patients who will not voluntarily swallow, an esophageal balloon fixed to a gastric tube is easier to place than an esophageal balloon on a narrow-bore catheter.

PATIENT VERSUS VENTILATOR WORK OF BREATHING

Patients often exert work during mechanical ventilation, particularly during assisted and spontaneous modes (e.g., pressure support, SIMV, A/C). The work performed by the patient may be high and difficult to assess by usual means such as contraction
of accessory muscles and asynchronous breathing. Measuring esophageal pressure, proximal airway pressure, and flow (integrated to volume) makes it possible to estimate the amount of inspiratory work done by the ventilator and the amount done by the patient. The area of the pressure-volume curve measured at the proximal airway during controlled ventilation represents the inspiratory work done by the ventilator (Fig. 27-9). The area of the pressure-volume curve measured using esophageal pressure represents the inspiratory work done by the patient

\[ W = \int P V \, dt \]

(Fig. 27-12). The sum of ventilator work and patient work is the total inspiratory work of breathing.

Some bedside monitoring systems calculate and display these measurements on a breath-by-breath basis (e.g., Bicore), which allows the clinician to titrate the level of respiratory support to the desired workload. Normal inspiratory work of breathing is

\[ \text{lower-inflation (PEEP)} \]

\[ \text{upper-inflation (overdistension)} \]

\[ \text{volume} \]

\[ \text{pressure} \]
Figure 27-12  Esophageal pressure-volume curve during spontaneous breathing (Campbell diagram). The slope of the pressure-volume curve during spontaneous breathing represents lung compliance. The chest wall compliance line is the slope of the esophageal pressure-volume curve generated during passive positive pressure ventilation. The area between the lung compliance line and the chest wall compliance line represents elastic work of breathing (shaded area). The area between the lung compliance line and the inspiratory pressure-volume curve represents the resistive work of breathing (cross-hatched area). The total spontaneous inspiratory work of breathing is the sum of the resistive work and the elastic work.

0.5 J/L (0.05 kg·m/L). High inspiratory work (>1.5 J/L or >15 J/L/min) results in fatigue and failure to wean from mechanical ventilation. Patient work can also be assessed by observing the esophageal pressure decrease during inspiration (Fig. 27-13). A pleural pressure change greater than 40 percent of the MIP indicates that fatigue is likely.

AUTO-PEEP WITH SPONTANEOUS BREATHING
During passive ventilation, auto-PEEP can be assessed by use of an end-expiratory hold (Chap. 26). During spontaneous breathing by the patient, an esophageal balloon is needed to assess auto-PEEP. With a spontaneous inspiration, inspiratory flow will not occur at the proximal airway until the pleural pressure change equals the auto-PEEP level. Auto-PEEP can thus be quantified by observing the pleural pressure change required to produce flow at the proximal airway (Fig. 27-14). Because auto-PEEP may be a fatiguing load for the spontaneously breathing patient, methods should be used to decrease the amount of auto-PEEP (e.g., application of external PEEP, administration of bronchodilators) (Chap. 7).

TRANSMISSION OF PRESSURE TO THE PLEURAL SPACE
Esophageal pressure measurements can also be used to estimate the amount of airway pressure transmitted to the pleural space during passive positive-pressure ventilation. The pleural pressure produced during passive inflation depends upon tidal volume and chest wall compliance. If the lungs are passively inflated, chest wall compliance can be calcu-
Figure 27-14 Use of esophageal pressure to estimate auto-PEEP during spontaneous breathing. The esophageal pressure change between “a” and “b” is the auto-PEEP level (a = onset of inspiration; b = onset of flow at airway).

BIBLIOGRAPHY


POINTS TO REMEMBER

- Much qualitative information can be obtained by observing the airway pressure waveform.
- Failure of the expiratory flow to decrease to zero indicates the presence of auto-PEEP; auto-PEEP may also be present even if expiratory flow is apparently zero at end-expiration.
- With a large leak from the lungs (around airway cuff or through bronchopleural fistula), expiratory volume will be less than inspiratory volume.
- Flow-volume loops can be used to assess response to bronchodilators.
- Pressure-volume loops can be used to assess trigger work, lung compliance, work performed by the ventilator during inspiration, appropriate PEEP setting, and hyperinflation.
- Esophageal pressure changes reflect pleural pressure changes.
- Esophageal pressure can be used to assess patient work of breathing, auto-PEEP during spontaneous breathing, and chest wall compliance.