BOX 8.6 Calculation of Alveolar Ventilation in VC-IMV

Calculations are made using the following data:
- Intermittent mandatory ventilation (IMV) rate = 5 breaths/min
- Tidal volume (V_T) = 600 mL
- Anatomical dead space (V_{Danat}) = 100 mL
- Added mechanical dead space (V_{Dmech}) = 50 mL
- Mandatory alveolar ventilation per minute ($\dot{V}_A$) = 5 × [600 − 100 − 50] = 2250 mL or 2.25 L/min
- Patient spontaneous rate = 10 breaths/min
- Spontaneous V_T = 350 mL
- Spontaneous alveolar ventilation = 10 × [350 − 100 − 50] = 2000 mL or 2 L
- Total alveolar ventilation = 2.25 + 2 = 4.25 L/min

measured near the patient's upper airway, because this eliminates the effects of the humidifying device and the breathing circuit on the measurement. Proximal pressure measurements are obtained by connecting the monitor tubing (usually a small-diameter plastic tube) to the Y-connector of the patient circuit. If the tubing is not visible on the circuit, pressures are detected through the main patient circuit and not at the upper airway. Although these values are not measured at the proximal airway, p ventilators are generally accurate and clinically useful[1] (Key Point 8.3).

Key Point 8.3 Proximal pressure and flow monitor lines must be free of moisture and secretions to provide accurate readings.

Pressure monitoring allows the clinician to assess pressure delivery to the upper airway. It ensures that a minimal pressure is maintained (low-pressure limit) and that high-pressure limits are not exceeded during mechanical ventilation. Intermittent readings of PIP, P_{plat}, set pressure (for pressure-targeted modes such as PC-CMV and pressure support), transairway pressure (P_{TA} = PIP − P_{plat}), mean airway pressure P_{aw}, and end-expiratory pressure (EEP) can provide valuable information about the patient's condition.

Peak Inspiratory Pressure

PIP (or P_{peak}), which is the highest pressure observed during inspiration, can be used to calculate dynamic compliance (C_D; also called *dynamic characteristic*). A fairly constant V_T with an increasing P_{peak} may indicate a reduction in lung compliance (C_L) or an increase in R_{aw}. Conversely, a declining PIP may indicate a leak or may be a sign of improvement in compliance or resistance.

Plateau Pressure

A P_{plat} reading can be obtained by using the ventilator's inspiratory pause control or setting a pause time of about 0.5 to 1.5 seconds. Remember that the static pressure is read when no gas flow is occurring. Traditionally, P_{plat} was determined by occluding the ventilator's expiratory port at the end of inspiration and reading the pressure registered on the ventilator's pressure manometer. After PIP is reached, the manometer needle or pressure indicator shows a drop of a few centimeters from peak and then briefly remains in a plateau (static) position before dropping

Key Point 8.4 Current practice strongly recommends keeping P_{plat} below 30 cm H_2O to avoid ventilator-induced lung injury.

to zero (see Fig. 8.3). It is important to remember that P_{plat} cannot be measured accurately if the patient makes active respiratory efforts, has a high f, or resists extending T_I; therefore, measurement of P_{plat} is difficult, if not impossible, to obtain in spontaneously breathing individuals.

P_{plat} is most often used to calculate C_S, which reflects the elastic recoil of the alveoli and thoracic cage against the volume of air in the patient's lungs. Current practice strongly recommends keeping P_{plat} below 30 cm H_2O (Key Point 8.4). Notice that during either pressure or volume ventilation, if a condition of no gas flow occurs near the end of inspiration (i.e., the flow−time waveform graphic shows a reading of zero), the corresponding pressure on the pressure-time curve is an indicator of P_{plat} (Fig. 8.4 and Key Point 8.5).

Key Point 8.5 Remember that flow occurs because of a pressure difference between two points. If the pressure is the same at any two points within a tube or conductive airway, no flow will occur between those points.

Set Pressure

During PC-CMV, PC-IMV, and PSV the operator sets a target pressure to be delivered to the patient. As shown in Fig. 8.1, many institutions include a separate space on the flow sheet for entering the target pressure.

Transairway Pressure: PIP Minus P_{plat}

The difference between the PIP and P_{plat} readings (PIP − P_{plat}) is the transairway pressure (P_{TA}). P_{TA} is the amount of pressure required to overcome R_{aw} ($R_{aw} = P_{TA}$/Flow). Notice that P_{TA} includes the resistance of the ET. A higher than expected difference between PIP and P_{plat} suggests an increased R_{aw}. R_{aw} most often increases when the patient's airway requires suctioning, the patient is biting the tube or it is kinked, or the patient has mucosal edema or bronchospasms (or both). It may also increase if the HME is partially occluded by accumulation of moisture or secretions.

Mean Airway Pressure

Many of the newer microprocessor-controlled ventilators automatically calculate and display $\overline{P}_{aw}$. $\overline{P}_{aw}$ is affected by PIP, end-expiratory pressure, the duty cycle (T_I/total cycle time [TCT]), and f. Inspiratory flow patterns and modes can also influence $\overline{P}_{aw}$. Monitoring $\overline{P}_{aw}$ can be useful when examining the benefits and side effects of positive pressure ventilation because it closely parallels the mean alveolar pressure. As discussed later in Chapter 13, the $\overline{P}_{aw}$ influences tissue oxygenation and affects both lung volumes and cardiac output. (See Chapter 13 for additional information for the calculation of $\overline{P}_{aw}$.)

End-Expiratory Pressure

End-expiratory pressure (EEP) is the lowest pressure measured during the expiratory phase of a breath. The EEP is above atmospheric pressure when $PEEP_E$ or CPAP is administered. EEP is also elevated when auto-PEEP occurs.

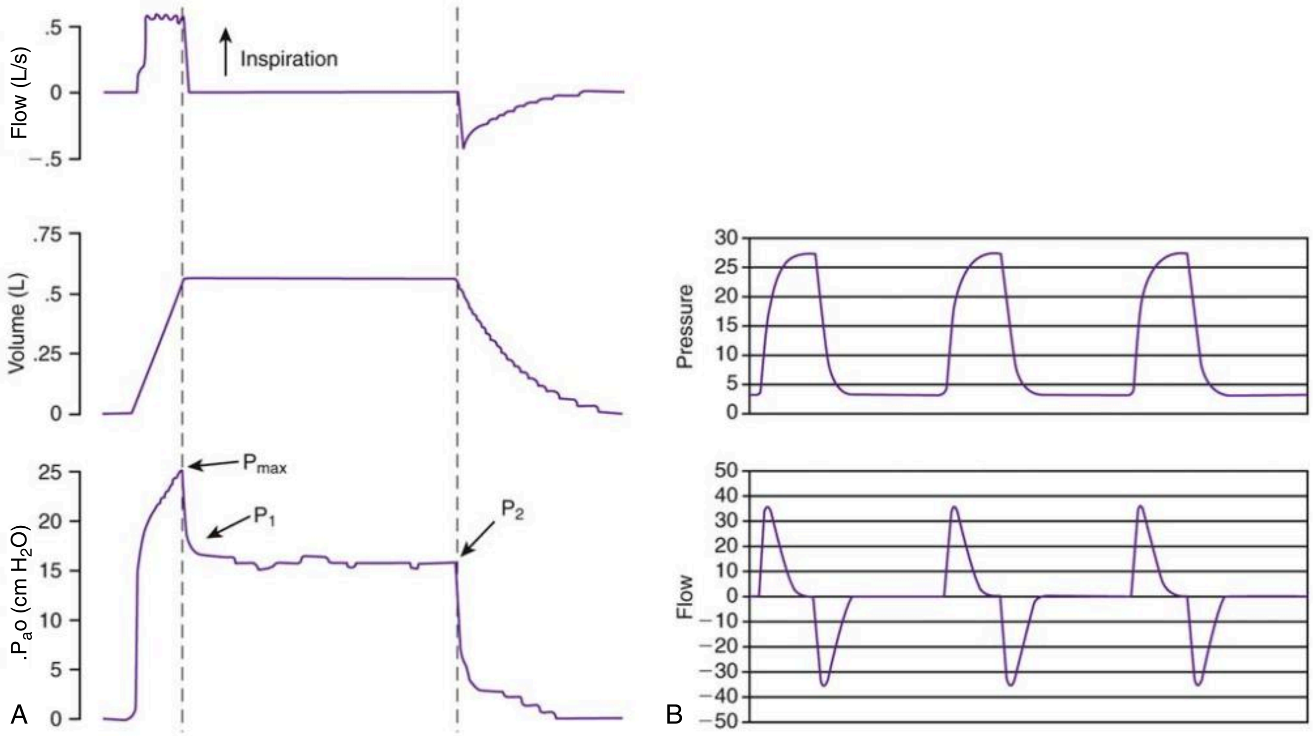


Fig. 8.4 (A) VC-CMV with an inspiratory pause set. *Top curve,* Flow-time curve. *Middle curve,* Volume-time curve. *Bottom curve,* Pressure-time curve. After PIP, P_{max} is reached and the pressure drops to a plateau (begins at P_1 and ends at P_2). At the same time, inspiratory flow delivery ends and the flow drops to zero. The exhalation valve does not open until the end of the pause time. Expiratory flow does not occur until then. (B) PC-CMV in which flow drops to zero during inspiration before the exhalation valve opens. The pressure measured during the no-flow period is an indicator of P_{plat}. (NOTE: For a plateau to be visible in PC-CMV, T_I must be long enough to allow ventilator pressure and lung pressure to equilibrate. If no pressure difference exists, no flow occurs.) (A from Pelosip P, Cereda M, Foti G, et al.: Alterations of lung and chest wall mechanics in patients with acute lung injury: effects of positive end-expiratory pressure, *Am J Respir Crit Care Med* 152:531—537, 1995. B from MacIntyre NR, Branson RD: *Mechanical ventilation,* ed 2, Philadelphia, PA, 2009, Saunders.)

An expiratory pause maneuver can be used to measure auto-PEEP, and most ventilators have a control for this purpose. The expiratory pause typically lasts 0.5 to 1.5 seconds, but some ventilators allow a pause of up to 15 to 20 seconds. As with the P_{plat} measurement, the EEP reading is accurate only if the patient is *not* actively breathing.

Sometimes the total PEEP ($PEEP_{TOT}$), which is the sum of the $PEEP_E$ and auto-PEEP, is recorded on the flow sheet. It is important to understand that $PEEP_{TOT}$ must be subtracted from P_{plat} to calculate C_S and from PIP to calculate C_D (Key Point 8.6).

An airway pressure slightly greater than zero can occur at the upper airway during exhalation if a constant gas flow is moving through the circuit. This constant flow is referred to as *bias flow* or *base flow.* It is used to help the ventilator detect flow changes during exhalation and allow flow triggering (see Chapter 3).

In most modern ventilators, bias flow occurs only at the end of exhalation; consequently, no resistance to flow exists at the beginning of exhalation. (Microprocessor-controlled ventilators include software that corrects for bias flow, which does not appear in the graphics for the pressure-time and flow-time curves.) For example, the Vyaire LTV 1000 ventilator (Vyaire Medical Inc.) has a constant bias flow of gas during exhalation of 10 L/min. Note that a flow of 10 L/min is the current base flow for the LTV 1000. The manufacturer may change this value in the future. The presence of bias flow is usually not clinically significant and does not cause increased resistance to exhalation except in small infants, in whom it can increase WOB.

***Key Point* 8.6** $PEEP_{TOT}$ must be subtracted from P_{plat} to calculate C_S, and from PIP to calculate C_D.

Driving Pressure

Driving pressure is the pressure difference between P_{plat} and total PEEP (PEEP plus auto-PEEP). It has been proposed that the driving pressure represents the distending pressure and therefore reflects the amount of energy applied to the lung. Thus, the higher the distending pressure applied to the lung, the greater the potential for lung injury.[8,9] It has been suggested that the driving pressure should be maintained below 15 cm H_2O as part of lung protective strategies used in the treatment of ARDS (see Chapter 13 for additional information related to the treatment of ARDS).

Pressure Limit

Audible and visual alarms are activated if PIP exceeds a set limit (this setting usually is about 10 cm H_2O above PIP). Activation of the high-pressure limit alarm ends inspiration. Some newer ventilators have an alarm delay that allows the limit to be exceeded for two or three breaths before the audible portion of the alarm is activated. It is worth noting, however, that in instances in which the pressure limit is exceeded, the breath ends and flow to the patient stops for that breath.

It is important to recognize that although high-pressure alarms are frequently activated when the patient coughs, activation of the alarm may indicate an increase in R_{aw} or a decrease in C_L. As mentioned earlier, increases in R_{aw} may signal that the patient's airway needs suctioning, that bronchospasm is occurring, or that the patient is biting the tube. Decreased C_L is associated with a number of conditions, such as pulmonary edema, pneumonia, pleural effusion, and pneumothorax.

BOX 8.7 False Pressure Readings or Alarm Failure

False pressure readings can occur if the tubing leading to the pressure indicator (whether digital or an analog manometer) is twisted or plugged with water or secretions. This is especially true for ventilators with plastic monitoring tubes that attach close to the Y-connector (proximal pressure lines). These monitoring lines measure pressure and may also detect flow, which in some cases is used to trigger the ventilator.

Manufacturers typically use air purging to maintain the patency of these monitoring lines. They also recommend that connection tubes are mounted above the endotracheal connection to prevent entry of water and secretions. Regardless of the setup, respiratory therapists should be vigilant about checking this type of monitoring system.

Case Study 8.2

Circuit Disconnect

The cardiac monitor on a mechanically ventilated patient suddenly activates. The patient demonstrates sinus tachycardia. The nurse and respiratory therapist check the patient but do not immediately find the cause of the tachycardia. The nurse pulls back the bedding sheet covering the patient's upper chest and discovers that the patient is disconnected from the ventilator. What probably prevented the ventilator's low-pressure alarm from activating?

Low-Pressure Alarm

Audible and visual alarms alert the clinician when PIP falls below a designated level (this setting is usually 5–10 cm H_2O below PIP). These alarms indicate that the pressure has fallen significantly and are usually associated with a leak in the patient-ventilator circuit. The most common cause of a leak is patient disconnection from the ventilator, which typically can be easily seen and quickly corrected. If a leak in the patient-ventilator circuit is not obvious, the patient must be manually ventilated with a resuscitation bag until the respiratory therapist can identify the cause of the leak (Box 8.7 and Case Study 8.2).

Checking the Circuit: Checking for Leaks

Evaluation of the integrity of the ventilator circuit is part of a standard ventilator check. It includes checking for leaks, disconnected tubing, and other circuit problems.

A leak can be identified in a number of ways. The simplest way is to note whether the peak pressure and exhaled volume are lower than previous measurements. The volume-time waveform can also be checked; if it resembles an igloo, the inspired V_T is greater than the expired V_T (Fig. 8.5).

To find a leak, the practitioner first should check the patient's airway by listening over the trachea with a stethoscope to determine whether the ET or tracheostomy tube cuff is adequately inflated. (If the cuff is not adequately inflated, abnormal breathing sounds will be heard as air leaks around the ET.) The clinician should then check for leaks in the ventilator circuit, starting at the point where the patient circuit attaches to the ventilator outlet and working toward the exhalation valve. Before beginning the test, it is prudent to hyperventilate and hyperoxygenate the patient. The patient is then disconnected from the ventilator and his or her lungs are manually ventilated with a resuscitation bag by another respiratory therapist or a nurse (Key Point 8.7).

Key Point 8.7 Disconnecting a patient from the ventilator can result in hypoventilation, hypoxemia, bradycardia, and/or hypotension. Before disconnecting the patient, it is prudent to hyperventilate and hyperoxygenate to reduce the risk for these complications.[2]

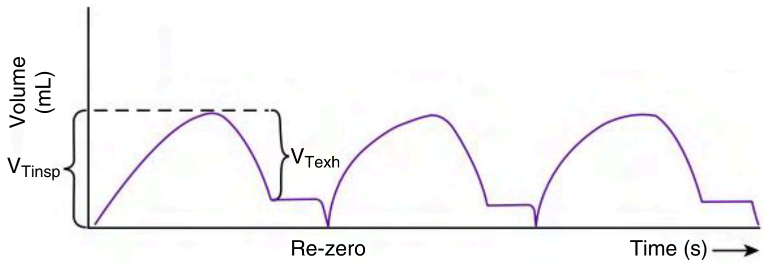


Fig. 8.5 Volume-time waveform during VC-CMV. Note that inspired tidal volume (V_{Tinsp}) is greater than expired V_T (V_{Texh}). All the volume measures are the same; therefore the leak is constant. Note that the software program for this waveform causes the line to drop to baseline before another breath is delivered.

The procedure for identifying the origin of a leak is fairly straightforward. First, the Y-connector is occluded and the ventilator is cycled. If the high-pressure limit is not reached, a significant leak is present. Second, the main inspiratory tubing on the distal side of the humidifier (the side farthest from the ventilator) is pinched closed. If the PIP alarm sounds, a leak does not exist in the humidifier system between the respiratory therapist's hand and the ventilator. If the alarm does not sound, the leak is in the humidifier assembly or at the point where the circuit attaches to the ventilator or to the humidifier. Third, the large-bore expiratory line is pinched shut and the ventilator is cycled manually. If the PIP limit alarm fails to activate, the leak is located near the Y-connector. This technique works well for large leaks but may not be as useful for identifying smaller leaks.

Leaks most often occur around the humidifier, through humidifier water-feed lines, at water traps, or anywhere tubing connections join. Other possible sources are closed-suction catheters, in-line thermometers, and end-tidal carbon dioxide (CO_2) monitors. A normal leak may be present around the ET if the minimum leak technique (MLT) is used to inflate the cuff (Box 8.8[10,11] and Case Study 8.3). The leak associated with the MLT is usually insignificant, and little volume is lost with adult patients. A chest tube may be another source of leaks. A pleural drainage system is a likely source if a leak is detected with the volume-time waveform but cannot be found in the circuit.

BOX 8.8 Minimum Leak and Minimum Occlusion Techniques for Cuff Inflation

Two techniques are commonly used to inflate tube cuffs:

1. *Minimum occlusion technique (MOT).* The cuff is inflated during positive pressure ventilation until no leak is heard at end inspiration. The leak is detected by listening with a stethoscope over the suprasternal notch or lateral neck. With MOT, just enough measured volume is injected into the cuff to stop all leakage around the cuff, resulting in the lowest cuff pressure needed to create a seal. The required volume is then recorded. (NOTE: Increasing the volume to slightly above that needed to occlude the airway can significantly increase cuff pressure.)
2. *Minimum leak technique (MLT).* The cuff is inflated during positive pressure ventilation until a leak is no longer heard on inspiration. A small amount of air is removed from the cuff so that the leak can just be heard at end inspiration. Some clinicians prefer MOT because of concerns about aspiration with MLT. Although MLT can provide low cuff pressures in some situations, it cannot do so if the cycling pressure necessary to achieve tidal volume (V_T) delivery is too high. This occurs in patients with low lung compliance (C_L) or high airway resistance (R_{aw}), in which case a significant amount of volume may be lost. A solution may be simply to increase the set volume on the ventilator to compensate for the volume loss. During VC-CMV, the amount of the leak that occurs with MLT changes as the peak inspiratory pressure (PIP) changes. If MLT is used when PIP is high and PIP gradually decreases, cuff volume eventually becomes higher than necessary. The leak actually may be eliminated, and MLT would have to be performed again. Conversely, if MLT is used at low PIP, the leak becomes too great if P_{peak} increases (see Case Study 8.3).

Case Study 8.3

Cuff Inflation Techniques

The minimum leak technique (MLT) has been used to establish cuff inflation with a cuff pressure of 20 mm Hg. At this same time (13:00), the respiratory therapist records a ventilator peak inspiratory pressure (PIP) of 28 cm H_2O, a set volume of 520 mL, and a measured exhaled volume of 500 mL. At 21:00 the PIP is 23 cm H_2O and the exhaled volume is 520 mL. What might account for an increase in volume while the pressure is decreasing?

A system leak can prevent flow cycling during PSV. For example, during PSV with the Servo-i ventilator, inspiration is adjusted to end when the flow falls below 5% of the peak inspiratory flow. If a leak in the system allows flow out of the circuit greater than 5% of the peak flow rate, the ventilator continues inspiratory gas flow to the patient. Most microprocessor-controlled ventilators have a backup cycling time of 1.5 to 3 seconds to end inspiration, if flow does not drop the set amount.

It is critical that no leaks exist in the ventilating system when expired gas is collected for measurements of the dead space—to—tidal volume ratio (V_D/V_T), oxygen (O_2) consumption per minute ($\dot{V}O_2$), and carbon dioxide (CO_2) production per minute ($\dot{V}CO_2$) (see Chapter 10). In these situations, it is necessary for the cuff to be sufficiently inflated to occlude the airway completely. Once the measurements have been obtained, the cuff should be reinflated using MLT or reinflated to the previous low pressure.

VITAL SIGNS, BLOOD PRESSURE, AND PHYSICAL EXAMINATION OF THE CHEST

Observing and recording a patient's vital signs (i.e., systemic arterial blood pressure [BP], heart rate [HR], temperature [T], breathing frequency (f), O_2 saturation measured by pulse oximetry [S_pO_2], and physical appearance) can help staff members evaluate possible changes in the patient's overall condition. In mechanically ventilated patients, f, HR, and S_pO_2 are monitored continuously. Temperature and arterial BP may also be monitored continuously, but more often they are measured intermittently. It is important for the clinician to remember that alarms are activated only by critical changes. Moderate changes in vital signs during hourly or bihourly checks should alert the practitioner to the possibility of hypoxemia, impending cardiovascular collapse (decreased or increased BP and HR), or infection (elevated temperature).

Heart Rate

An electrocardiogram (ECG) is a noninvasive means of continuously monitoring HR and heart rhythm. All hospitalized patients receiving ventilatory support must be continuously monitored with a three-lead ECG. The ECG provides minimum and maximum HR alarms (audible and visual) and therefore can alert the ICU staff if significant bradycardia or tachycardia occurs.

The ECG leads are generally placed on the chest, one near each clavicle and one near the fourth intercostal space at the left midaxillary line. It is important to place the leads so that a clearly discernible QRS complex can be displayed on the monitor (a standard lead II configuration is typically used for monitoring ICU patients).

The ECG monitor is viewed or scanned by a computer for changes in HR and rhythm. Activation of an audible alarm alerts personnel when a potentially dangerous event has occurred. Activation of the HR alarm may simply indicate that the ECG electrodes have become disconnected from the patient, or it may signal a more critical event (e.g., the patient has become disconnected from the ventilator and is experiencing severe hypoxemia, hypercapnia, or both). Other factors that can affect HR include pathological changes in the myocardium (e.g., infarction, hypoxia, and drug reaction), anxiety, pain, and stress. An initial 12-lead ECG should be obtained when mechanical ventilation is initiated in patients older than 21 years with acute respiratory failure.[3]

Temperature

A patient's temperature can be measured orally (by mouth), aurally (by ear), or by an axillary technique (from the armpit). Core temperature measurements are typically obtained using rectal, esophageal, or pulmonary artery temperatures. A number of factors can affect body temperature.[12] For example, hyperthermia can be caused by infection, tissue necrosis, late-stage carcinoma, Hodgkin disease, leukemia, and metabolic abnormalities, such as hyperthyroidism. Low-grade fever can be a result of accidental or surgical trauma, atelectasis, fistulas, hematomas, or foreign bodies.

Hypothermia can result from metabolic diseases (e.g., hypothyroidism), central nervous system disorders, drugs (e.g., phenothiazines, tricyclic antidepressants, and benzodiazepines), and other substances (e.g., alcohol, heroin, carbon monoxide).[12]

Systemic Arterial Blood Pressure

A patient's BP should be checked intermittently with a stethoscope and sphygmomanometer or an automatic BP cuff. It can also be measured continuously with invasive intravascular arterial catheters. Invasive arterial pressure monitoring is typically used after open heart surgery and for critically ill patients requiring continuous, direct measurements of BP (see Chapter 11).

Arterial catheters are usually placed in a peripheral vessel, such as the radial artery, where collateral circulation exists. A modified Allen's test (Box 8.9) should be performed whenever a radial artery catheter is placed.

Central Venous Pressure

Indwelling venous catheters placed in the superior vena cava or right atrium can be used to monitor central venous pressure (CVP), myocardial function, and fluid status in critically ill patients (see Chapter 11). CVP measurements reflect right arterial pressure and right ventricular end-diastolic pressure and therefore can provide valuable information about venous return and right heart function.

Because CVP is elevated during a positive pressure breath, it is measured at the end of expiration when intrapleural pressure returns to normal or its lowest value during the respiratory cycle.

Pulmonary Artery Pressure

Pulmonary artery pressure can be monitored continuously with a balloon-tipped, flow-directed, pulmonary artery (PA) catheter that is connected to a monitor by a transducer. PA catheters are typically used to monitor the hemodynamic status of critically ill patients with severe cardiopulmonary complications and problems with fluid management (see Chapter 11).

Physical Examination of the Chest

Ideally, physical examination of a patient should be performed at least once every shift. This examination should include inspection, palpation, percussion, and auscultation of the chest. The results are recorded on the chart and compared with previous findings. Abnormal findings or significant changes must be evaluated and treated promptly.

Different conditions can produce a variety of physical findings (e.g., hyperresonance occurs on chest percussion of a patient with severe asthma and air trapping). Additionally, breath sounds and chest excursion are diminished, accessory muscle use is increased, and high-pitched wheezes are present. For patients with pneumonia, the chest is dull to percussion, breath sounds are decreased, and crackles (rales) occur late in inspiration over the affected area. With pleural effusion, the affected area produces a dull percussion note, breath sounds are absent, and a pleural friction rub may be audible on auscultation. Patients with a large pneumothorax show a shift in their tracheal position away from the affected side. Chest percussion in these patients is hyperresonant over the affected area, and breath sounds are absent. Table 8.1 presents a list of the physical changes associated with various pulmonary disorders.

Auscultation of the chest that reveals low-pitched breath sounds with a rattle-like quality (rhonchi) may indicate secretions in the larger airways and the need for suctioning. The presence of wheezes often suggests the need for bronchodilator therapy, although wheezes can also occur when secretions are retained in the small airways and with some cardiac conditions. Absence of breath sounds may indicate a pneumothorax, complete airway obstruction, complete lung collapse, improper placement of the ET, or a pleural effusion. Evaluation of both the physical and ventilatory findings (e.g., increased PIP, chest radiograph results) can confirm the presence of abnormal findings and point to appropriate treatments.

Patient assessment should also include evaluation of respiratory muscle use. Increased use of the accessory muscles of inspiration or *paradoxical breathing* (retraction of the abdomen during inspiration and protrusion during exhalation) indicates an increased WOB and the potential for respiratory muscle fatigue.[13]

Abdominal distention suggests several problems, including postoperative intestinal accumulation of gas, air swallowing, bleeding, or **ascites** (fluid in the abdominal space). Regardless of the cause, abdominal distention can impair ventilation by applying upward pressure on the diaphragm, creating restrictive breathing difficulties. The cause must be determined and the problem should be corrected if possible (Case Study 8.4).

BOX 8.9 The Modified Allen Test

The modified Allen test for collateral circulation is performed by holding a patient's hand with the palm up, occluding the radial and ulnar arteries, and having the patient open and close the hand. The hand is opened to make sure it is drained of blood (blanched), and the pressure over the ulnar artery is then released. The palm flushes with blood in 15 seconds or less if collateral circulation to the hand through the ulnar artery is present. The process is repeated with the radial artery to demonstrate perfusion in this vessel. Note that the modified Allen test results are not always reliable and the results must be interpreted with caution.

TABLE 8.1 **Physical and Radiological Findings in Common Pulmonary Disorders**

Diagnosis	Auscultation	Percussion	Tracheal Excursion	Chest Wall Movement	Chest Radiograph
Asthma	High-pitched wheezing	Hyperresonant R and L	WNL	↓ R and L	↑ Radiolucency
Pneumonia (R)	Late inspiratory crackles	Dull (R)	WNL; if massive, L-shift	↓ R	Infiltrates (R)
Pleural effusion (R)	Friction rub, just above fluid level	Dull (R)	L-shift	↓ R	Blunting of costophrenic angle (R)
Pneumothorax (R)	Decreased or absent on R	Hyperresonant (R)	L-shift	↓ R	Lack of vascular markings (R); mediastinal shift (L)
Emphysema	Diminished; vary; early expiratory crackles	Hyperresonant	WNL	↓ R and L	↑ Radiolucency; widened rib spaces; flattened diaphragm

↓, Decrease; ↑, increase; *L*, left; *R*, right; *WNL*, within normal limits.

Case Study 8.4

Patient Assessment Cases

Problem 1

Physical examination of a patient on mechanical ventilation reveals bilateral low-pitched lung sounds and normal resonance to percussion. The patient has a temperature of 39° C. Heart rate is 122 beats/min and blood pressure is 135/85 mm Hg. What is the possible cause of this patient's abnormal breath sounds? What therapeutic procedure is indicated?

Problem 2

On chest auscultation, the practitioner hears no breath sounds on the left but distant breath sounds on the right. The percussion note on the left is hyper-resonant, and the note on the right has normal resonance. The trachea is deviated to the right. During the past hour, cardiac output has dropped from 6 L/min to 4.5 L/min. What is the most likely problem?

Problem 3

A female patient has been intubated for 4 hours and is receiving 100% oxygen. Auscultation of the patient's chest reveals normal breath sounds on the right but no breath sounds on the left. The percussion note is normal on the right and dull on the left. The oral endotracheal tube indicates a 26-cm marking at the teeth. What is the most likely problem?

MANAGEMENT OF ENDOTRACHEAL TUBE AND TRACHEOSTOMY TUBE CUFFS

During the initial assessment of a ventilated patient, the respiratory therapist evaluates endotracheal and tracheostomy tube position, in addition to cuff integrity and pressures. The following section reviews the procedures for measuring cuff pressures and for dealing with inappropriate cuff pressures and cuff leaks.

Cuff Pressure Measurement

The endotracheal or tracheostomy cuff pressure is typically checked during the initial evaluation of the patient and once every 8 to 12 hours to ensure that cuff pressures do not exceed 20 to 25 mm Hg (27–34 cm H_2O). It is generally accepted that maintaining the cuff pressure below 34 cm H_2O (25 mm Hg) reduces the risk for tracheal damage associated with overinflated tube cuffs. Although the pressure transmitted to the tracheal wall is generally lower than the pressure in the cuff, some clinicians contend that using a low cuff pressure reduces the risk for tracheal damage and necrosis associated with tube cuffs.[13,14] Tracheal damage and necrosis can occur if the cuff pressure transmitted to the trachea is greater than the perfusion pressure. This is particularly important in hypotensive patients, in whom even an ET and tracheostomy cuff pressure of only 34 cm H_2O (25 mm Hg) can exceed the perfusion pressure to the trachea, resulting in significant tracheal damage.

Cuff pressure measuring devices are a convenient means of monitoring cuff pressure and for adding or removing air from the cuff. These devices have either an analog (gauge) or a digital readout (Fig. 8.6). A small volume of air is lost when the cuff pilot balloon is

Fig. 8.6 A Posey Cufflator manometer used to measure endotracheal tube cuff pressure. (From Cairo JM: *Mosby's respiratory care equipment*, ed 11, St. Louis, MO, 2022, Elsevier.)

Key Point 8.8 Suctioning the area around the ET above the upper limits of the ET cuff before deflating it can reduce the risk for the patient aspirating secretions that have accumulated above the cuff. These secretions, if aspirated into the lower airways, increase the risk for the patient developing a ventilator-associated pneumonia.

BOX 8.10 Improving the Accuracy of Cuff Pressures Measured With a Cuff Inflation Device

Modified from Blanch PB: Laboratory evaluation of 4 brands of endotracheal tube cuff inflator, *Respir Care* 49:166—173, 2004.

1. Place a stopcock into the pilot valve of the endotracheal tube (ET).
2. Set the stopcock to the closed-in-all-directions position.
3. Attach a cuff inflator and a syringe to the two open ports of the stopcock. (NOTE: The Cuffalator and the Endotest have their own bulbs, which can be used in place of a syringe.)
4. Turn the stopcock to the syringe or bulb to prepressurize the cuff inflator. (NOTE: If the device has a built-in inflator bulb, the stopcock can remain in the closed-in-all-directions position.)
5. Pressurize the cuff to 27 cm H_2O (20 mm Hg) using the syringe or bulb.
6. Once the cuff has been pressurized, rotate the position of the stopcock to connect the cuff inflator to the ET cuff.
7. If the cuff pressure is not approximately 27 cm H_2O (20 mm Hg), it will rise or fall, depending on the difference. The range should be 27 to 34 cm H_2O (20—25 mm Hg) or less.

connected to the device, because these devices use short connecting tubes. The pressure may be shown in centimeters of water (cm H_2O) or millimeters of mercury (mm Hg), depending on the device.[15] Unfortunately, these devices are often inaccurate, and clinicians may find it advisable to use an alternative method for measuring cuff inflation pressures (Box 8.10 and Key Point 8.8).[15]

ET and tracheostomy cuff pressures can also be measured using a mercury column manometer, like those used to measure BP. A three-way or four-way stopcock between the cuff pilot balloon and manometer should be used to pressurize the manometer before the cuff pressure is measured. If this is not done, a significant amount of the cuff volume or pressure will be lost in the connecting tube. Air is injected into the manometer with a syringe to pressurize it. The amount of pressure added must equal previous pressure readings or must be approximately 20 to 25 mm Hg (27—34 cm H_2O).[16] The cuff and manometer can be pressurized simultaneously if the cuff is being inflated or was deflated before measurement (Fig. 8.7).

The following five-step protocol was developed to minimize the risk for tracheal necrosis associated with cuff overinflation:

1. MLT should be used whenever possible.
2. A reasonable MLT should be established, one in which only 50 to 100 mL of V_T is lost during inspiration. For example, in VC-CMV with a 600 mL V_T setting and delivery, the exhaled V_T is 500 to 550 mL.
3. A high-volume/low-pressure cuff should not require more than 5 mL for inflation. If it does, the tube probably is too small.
4. If a minimal leak cannot be maintained with a cuff volume of less than 5 mL, the practitioner should make sure the cuff pressure is less than 25 mm Hg and that the

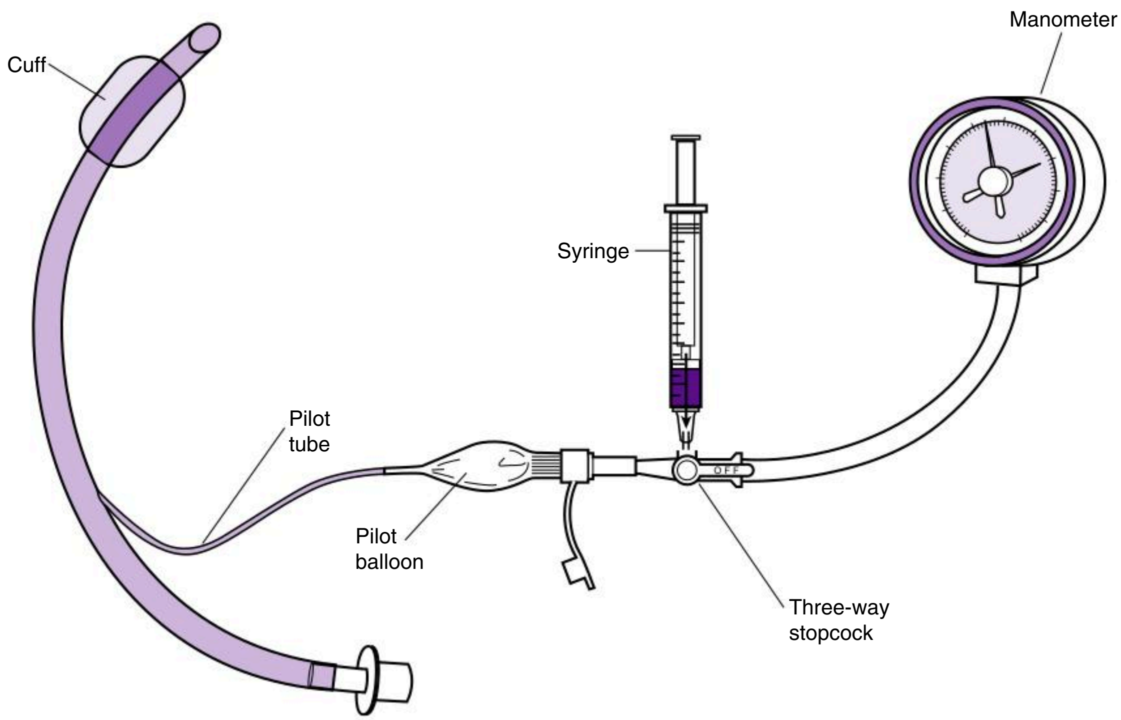


Fig. 8.7 A syringe, manometer, and three-way stopcock can be used to measure cuff pressure. (See text for explanation of procedure.)

cuff-to-tracheal diameter ratio checked on chest radiograph is 1:1.5 or less.

5. If steps 1 through 4 cannot be achieved, the patient should be followed for tracheal stenosis for at least 1 year after discharge.

High Cuff Pressure

The most common cause of an excessively high cuff pressure is simply an overinflated tube cuff. Occasionally cuff pressures are high because a low-volume/high-pressure cuff is used. However, most cuffs currently used are the high-volume/low-pressure type unless a specialty tube is used.

Occasionally, a higher than acceptable cuff pressure is required to maintain a minimum occlusion, and none of the problems previously mentioned are present. There are two reasons why this may occur. First, the cuff and artificial airway may have moved up (cephalad) in the patient's airway and become lodged in the larynx or pharynx. The markings at the lips or teeth may indicate the depth of the tube in the airway. In this situation, the tube should be moved farther into the airway. Second, the ET may be too small for the patient; in this situation, a large volume is required to seal the tube in the trachea. This is a particularly difficult problem because the clinician may be reluctant to change to a larger tube. However, if the ET will be needed for several days, changing it is the wise course. This can be done using a tube changer (Fig. 8.8). The tube changer is inserted into the current ET, which is removed while the changer is left in place. A larger ET is inserted over the tube changer and into the trachea, and the tube changer is then withdrawn.

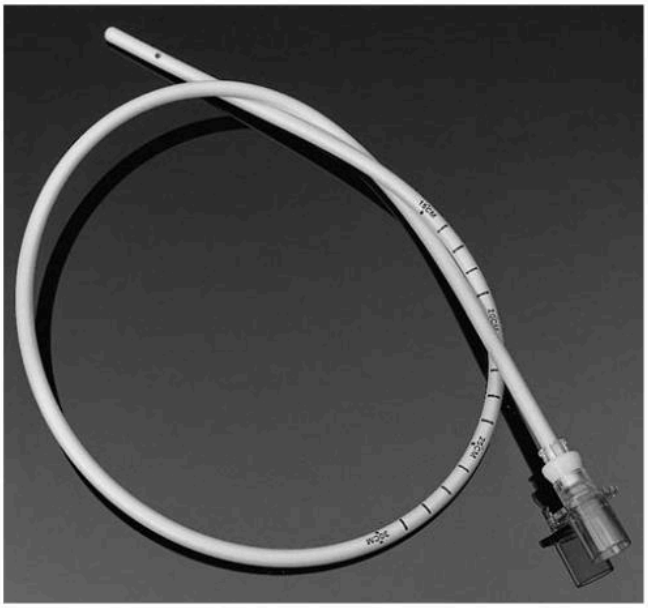


Fig. 8.8 Endotracheal tube changer (see text for further information). (From Cairo JM: *Mosby's respiratory care equipment,* ed 11, St. Louis, MO, 2022,Elsevier.)

On rare occasions a high cuff pressure may be required to maintain either a minimum leak or minimum occlusion because the patient's trachea is dilated at the level of the cuff (Fig. 8.9). Occasionally, the cuff can be repositioned, but a dilated trachea suggests that the cuff has been in place and overinflated for quite some time, resulting in the tracheal injury (see Case Study 8.3).

Nonexistent or Low Cuff Pressure

If the cuff pressure is low or nonexistent, the respiratory therapist should first check that the cuff has been properly inflated and is in the appropriate position in the airway. If the pressure is still low (or absent) or continues to drop after inflation and positioning, the most common cause is a leak in the ET cuff or pilot system. Fig. 8.10 presents an algorithm for determining the cause of a cuff leak and loss of pressure.[17,18]

The location of the leak must be determined. First, the cuff is inflated to an appropriate pressure and the pilot tube is clamped. The clinician then listens for an air leak in the upper airway. For example, if a leak is present during a positive pressure breath, air can be heard over the neck area or may even be escaping from the patient's mouth. If the cuff continues to lose pressure with the pilot tube clamped, the leak is probably in the cuff itself.

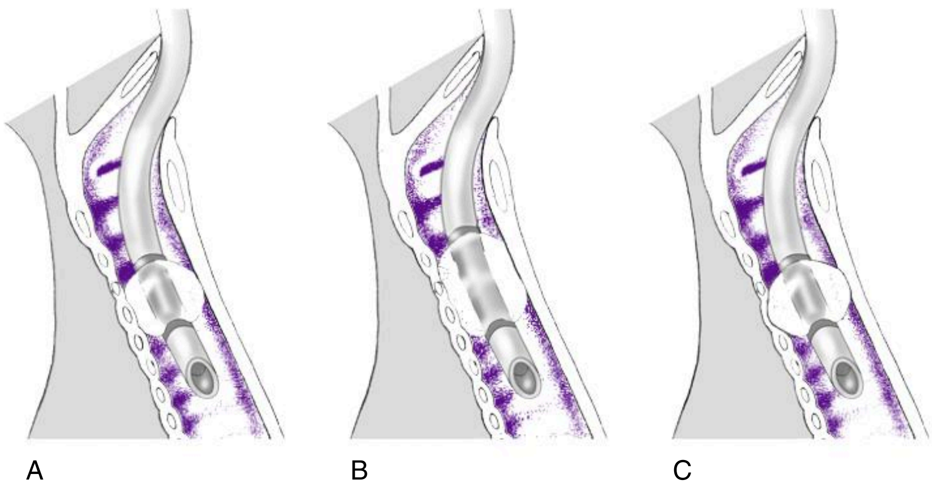


Fig. 8.9 (A) Low-volume/high-pressure cuff. (B) High-volume/low-pressure cuff. (C) Tracheal dilation adjacent to the cuff. (Modified from Hess DR, MacIntyre NR, Mishoe SC, et al.: *Respiratory care principles and practice,* Philadelphia, PA, 2002, WB Saunders.)

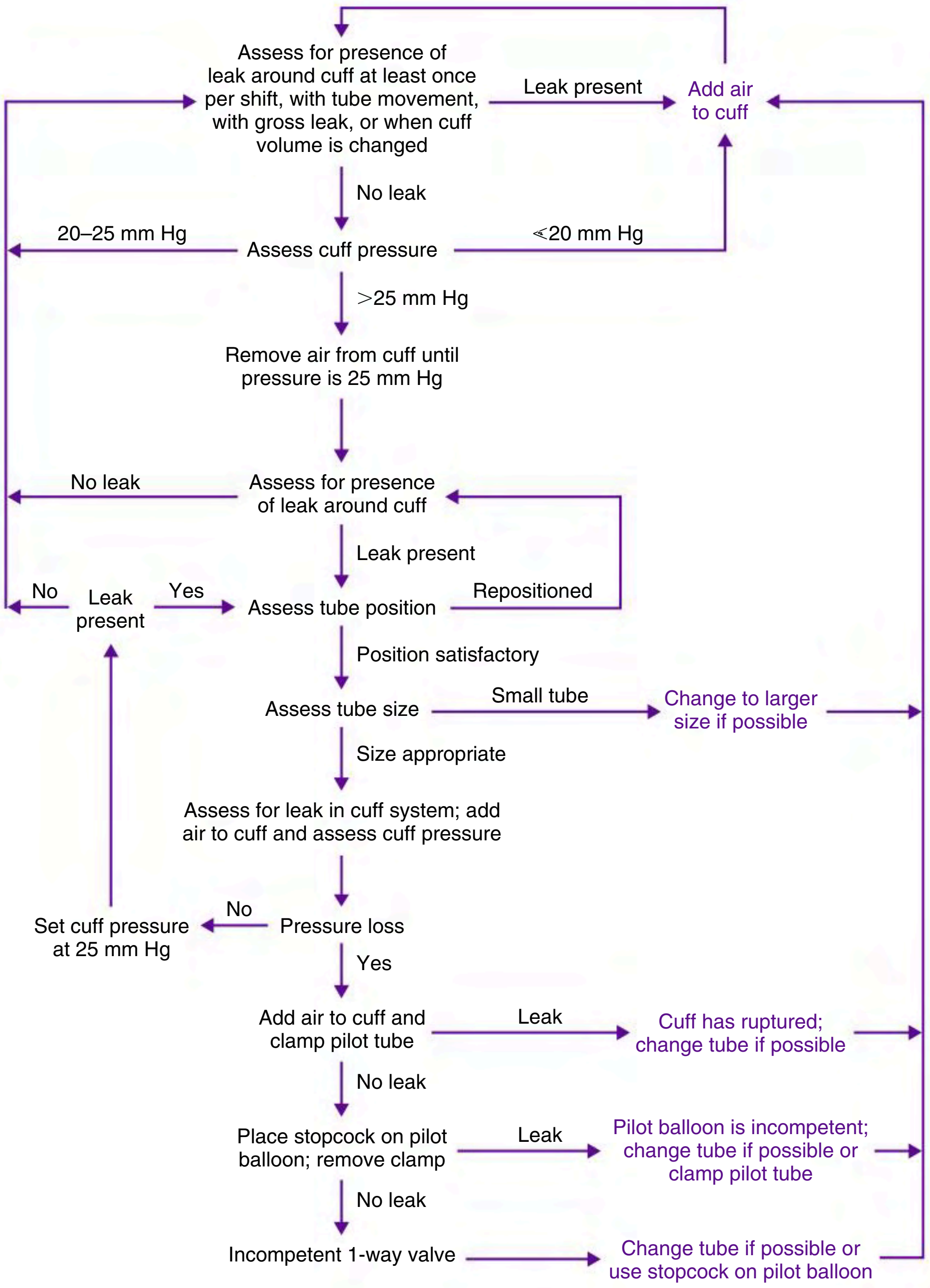


Fig. 8.10 Algorithm for resolution of a cuff leak in an artificial airway. (Modified from Hess DR: Managing the artificial airway, *Respir Care* 44:759—772,1999.)

If the leak is not in the cuff, it may be in the pilot balloon or the valve. To detect these types of leaks, the cuff is inflated and a stopcock is attached to the pilot balloon. The stopcock is turned to the off position. If the leak is still present, it is located in the pilot balloon. This problem can be solved temporarily by clamping the pilot line. If the stopcock on the pilot balloon resolves the leak, the valve is not working. Simply leaving the stopcock on the pilot balloon temporarily solves this problem. The tube should be changed if possible.

A 2-year study of massive airway leaks produced an important finding: a large number of ETs that were removed for apparent defects or damage were actually flawless. Tube malposition was the most likely explanation for these results. Careful investigation of a leaking airway should precede any decision to change the tube to solve the problem.[19,20]

Cut in the Pilot Tube

An accidental cut in the pilot tube is a common occurrence. This often happens when clinicians change the tape that secures the tube. This problem can be remedied by positioning a three-way stopcock between a blunt-tipped needle inserted into the cut

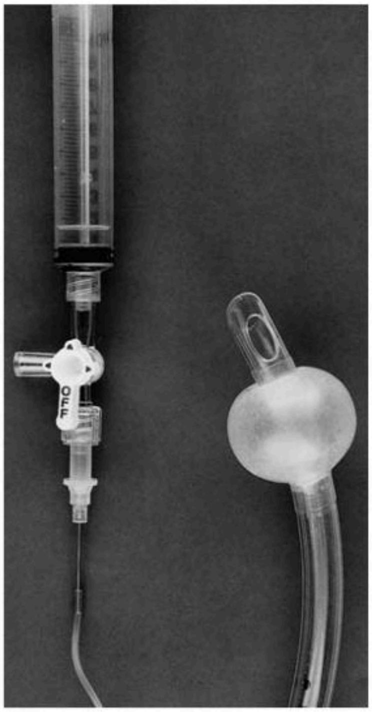


Fig. 8.11 A cut pilot tube can be repaired temporarily by inserting a cutoff 19-gauge needle with a stopcock into the pilot tubing. This system can also be used to repair a failed pilot balloon/valve assembly by cutting the pilot tube and inserting the needle.

pilot tube and a syringe (Fig. 8.11). Some manufacturers specifically design blunt-tipped needle devices with pilot balloons. The blunt-tipped needle can be inserted into the cut pilot tube, and the cuff of the ET can be inflated (Fig. 8.12).

Tube and Mouth Care

About once every shift (approximately 8–12 hours) the ET must be repositioned in the mouth and retaped if needed. Repositioning the ET helps prevent pressure injuries to the gums, mouth, lips, or nose that can occur as a result of the constant pressure of the tube. Oral hygiene should also be performed routinely. Although oral hygiene is typically the responsibility of the patient's nursing staff, respiratory therapists are often involved. The process of retaping and repositioning the tube is a two-person procedure. One practitioner holds the tube in place while the other person secures the tube with surgical tape.

Fig. 8.12 Pilot tube repair kit. (Courtesy Instrumentation Industries, Inc., Bethel Park, Pa.)

MONITORING COMPLIANCE AND AIRWAY RESISTANCE

Static Compliance

Normal C_S is approximately 70 to 100 mL/cm H_2O ($C_S = V_T/[P_{plat} - EEP]$). When C_S is less than 25 mL/cm H_2O, WOB is very high. The accuracy of the C_S calculation depends on the accuracy of the actual delivered V_T and P_{plat} measurements.

Chest wall recoil and the elastic recoil of the patient circuit remain fairly constant in most patients. A change in C_S readings over time is usually considered a result of change in the patient's alveolar elastic recoil.

In cases in which chest wall compliance does change, C_S readings can be used to identify the presence of a significant problem. For example, air trapping, pulmonary edema, atelectasis, consolidation, pneumonia, pneumothorax, hemothorax, and pleural effusion will cause a decrease in C_S. Reductions in chest wall compliance can also occur with flail chest, changes in chest wall muscle tension, pneumomediastinum, and abdominal distention (e.g., peritonitis, ascites, herniation, abdominal bleeding). Note that clinicians can also detect many of these conditions by evaluating breath sounds and percussion notes, palpating the chest and abdominal wall, obtaining a chest radiograph, and studying laboratory data.

Regardless of the method used to determine that an abnormal condition exists, appropriate medical intervention must be initiated and the problem corrected. Reduced C_S implies that ventilation is less effective. In PC-CMV, pressure remains constant, whereas the delivered V_T decreases. In VC-CMV, PIP and P_{plat} increase while the delivered V_T remains fairly constant (Table 8.2A and B). In PC-CMV, pressure must be increased when compliance decreases to maintain V_T delivery. Reduced C_S can result in a decreased P_aO_2 and an increased arterial carbon dioxide partial pressure (P_aCO_2); therefore determining the cause of the condition and treating it are important.

Dynamic Characteristic (Dynamic Compliance)

The **dynamic characteristic** (C_D), often called *dynamic compliance* or *dynamic effective compliance,* is the volume delivered by the ventilator divided by (PIP − EEP): C_D = Volume/PIP − EEP).[21] C_D is measured during airflow; therefore it is influenced by the patient's lung and chest wall elastic recoil and by airway resistance, the ET, and the ventilator circuit. Because C_D includes both compliance and resistance components, it is more accurately described as an impedance measurement; however, most practitioners still refer to it as dynamic compliance.

The C_D decreases whenever C_S decreases or R_{aw} increases. Decreases in lung elasticity can be easily differentiated from airway problems simply by monitoring changes in PIP, P_{plat}, and the difference between them (P_{TA}). If both PIP and P_{plat} are increasing with the same volume delivery and the P_{TA} is fairly constant, C_S is decreasing (see Table 8.2B and C). If PIP increases along with P_{TA}, R_{aw} is increasing (see Table 8.2D). Calculation of C_D and C_S confirms these findings.

With VC-CMV, volume delivery remains nearly constant regardless of changes in C_D; however, delivery pressures may

TABLE 8.2 Simplified Examples of Changes in Delivered Tidal Volume (V_T), Peak Inspiratory Pressure (PIP), and Pressure Plateau (P_{plat}) Reflecting Changes in Dynamic Compliance (C_D)

A. Decreasing C_D During PC-CMV

Time	PIP	V_T	C_D[a]
01:00	25	500	20
02:00	25	400	16
03:00	25	300	12

Constant pressures with decreasing volume.

B. Decreasing C_D During VC-CMV

Time	PIP	V_T	C_D
01:00	25	500	20
02:00	30	500	17
03:00	35	500	14

Constant volume with increasing pressures.

C. Decreasing C_S AND C_D During VC-CMV With Constant R_{aw}

Time	PIP	C_D	P_{plat}	C_S[a]	P_{TA}	Volume[b]
01:00	25	20	20	25	5	500
02:00	30	17	25	20	5	500
03:00	35	14	30	17	5	500

Increasing PIP and P_{plat}. Volume and pressure lost to the airways are constant. The lung is less compliant.

D. Decreased C_D, Constant C_S During VC-CMV With Increased R_{aw}

Time	PIP	C_D	P_{plat}	C_S	P_{TA}	Volume
01:00	25	20	20	25	5	500
02:00	30	17	20	25	10	500
03:00	35	14	20	25	15	500

Increasing PIP with constant volumes and P_{plat}. R_{aw} is increased (P_{TA} = PIP − P_{plat}).

E. Improving C_D and C_S During VC-CMV

Time	PIP	C_D	P_{plat}	C_S	P_{TA}	Volume
01:00	25	20	23	22	2	500
02:00	23	22	21	24	2	500
03:00	20	25	18	28	2	500

PIP and P_{plat} are decreasing, delivered volume and P_{TA} are constant, and the lungs are more compliant.

F. Compliance Measurements With PEEP During VC-CMV

Time	PIP	C_D	P_{plat}	C_S	P_{TA}	PEEP	Volume
01:00	30	20	28	22	2	+5	500
02:00	35	20	33	22	2	+10	500
03:00	40	18	37	20	3	+12	500

The addition of increasing PEEP results in increasing PIP and P_{plat}. Delivered V_T and P_{TA} remain constant.

[a]Volume is shown in mL throughout the table.
[b]Compliance is shown in mL/cm H_2O throughout the table.
C_D, dynamic compliance (C_D = Volume/[PIP − EEP]); *C_S,* static compliance (C_S = Volume/[P_{plat} − EEP]); *EEP,* end-expiratory pressure; *PEEP,* positive end-expiratory pressure; *PIP,* peak inspiratory pressure (cm H_2O); *PC-CMV,* pressure-controlled, continuous mandatory ventilation; *P_{plat},* plateau pressure (cm H_2O); *P_{TA},* transairway pressure (cm H_2O); *R_{aw},* airway resistance; *VC-CMV,* volume-controlled, continuous mandatory ventilation; *V_T,* tidal volume (mL).

become dangerously high. In PC-CMV, a decrease in C_D will result in a reduction in the delivered V_T. Pressure must therefore be increased to maintain the delivered V_T. During VC-CMV, a decreasing PIP with a constant delivered V_T may signal improvement in compliance or R_{aw} (see Table 8.2E). It is important to measure the delivered V_T because a decreasing pressure might also indicate a leak. Remember, if extrinsic PEEP ($PEEP_E$) and/or auto-PEEP is present, it must be subtracted from P_{plat} and PIP readings to calculate C_S and C_D (see Table 8.2F).

During PC-CMV, increased V_T delivery with the same pressure indicates an improvement in compliance or a decrease in R_{aw} (or both) (Case Study 8.5).

Airway Resistance

Total resistance is the sum of R_{aw} and tissue resistance, although tissue resistance remains relatively constant in most cases. (NOTE: Tissue resistance can increase in conditions such as ascites and pleural effusion.) R_{aw} normally ranges from 0.6 to 2.4 cm H_2O/L/s; it can be estimated for patients on ventilation patients by measuring P_{TA} and using the inspiratory flow and a constant flow waveform. Although this is not an accurate flow measurement, it can be used over time to indicate relative changes in R_{aw}. For example, if PIP is 35 cm H_2O, P_{plat} is 34 cm H_2O, and flow is 30 L/min (0.5 L/s), R_{aw} is calculated as follows:

$$R_{aw} = \frac{P_{TA}}{Flow}\left(\frac{L}{sec}\right)$$

$$R_{aw} = \left(\frac{PIP - P_{plateau}}{Flow}\right)$$

$$R_{aw} = \frac{(35 - 34 cmH_2O)}{\left(\frac{0.5L}{sec}\right)}$$

$$R_{aw} = \frac{2cmH_2O}{\frac{L}{sec}}$$

Case Study 8.5

Exercises

Problem 1

While checking the ventilation parameters during VC-CMV, you notice the following changes in positive inspiratory pressure (PIP) and plateau pressure (P_{plat}):

Time	Volume (L)	PIP (cm H_2O)	P_{plat} (cm H_2O)
01:00	0.7	23	15
03:00	0.7	28	16
05:00	0.7	35	17

What is the likely cause of the problem? How would you assess the patient to determine the appropriate treatment?

Problem 2

During PC-CMV, the following changes are noted:

Time	Volume (L)	Set Pressure (cm H_2O)
01:00	0.65	20
03:00	0.60	20
05:00	0.55	20

What is the likely cause of the problem? How would you assess the patient to determine treatment?

Many microprocessor-controlled ventilators use software programs that can calculate and display compliance and resistance values. Some of the values are taken from measurements of pressure, expired flow, and volume.

Treatment for increased R_{aw} must be directed at the specific cause of the increase. For example, suctioning the airway, clearing an obstruction, or giving a bronchodilator treatment may correct the problem.

Bedside Measurement of Pressure-Volume Curves

The pressure-volume relationships for C_D and C_S can be plotted by ventilating the lung at different volumes and recording the PIP and P_{plat}.[22,23] Bone and colleagues first described a bedside measurement technique for drawing static pressure-volume (P-V) curves more than 40 years ago.[20,22,23] Plotting of P-V curves is still a valuable tool (Fig. 8.13).[24] Box 8.11 explains the procedure for obtaining static P-V. Current ICU ventilators are equipped with computer software and graphic displays that can automatically generate P-V loops and save a reference loop to make comparisons over time. Daily evaluation of the pressure-volume relationship (either static or dynamic) is recommended to track progression of lung compliance and R_{aw} changes. (Chapters 9 and 13 contain additional information on P-V curves.)

Fig. 8.13 shows changes in the graphic waveforms that are often associated with patients demonstrating sudden hypoxemia caused by airway problems, lung parenchymal problems, and pulmonary

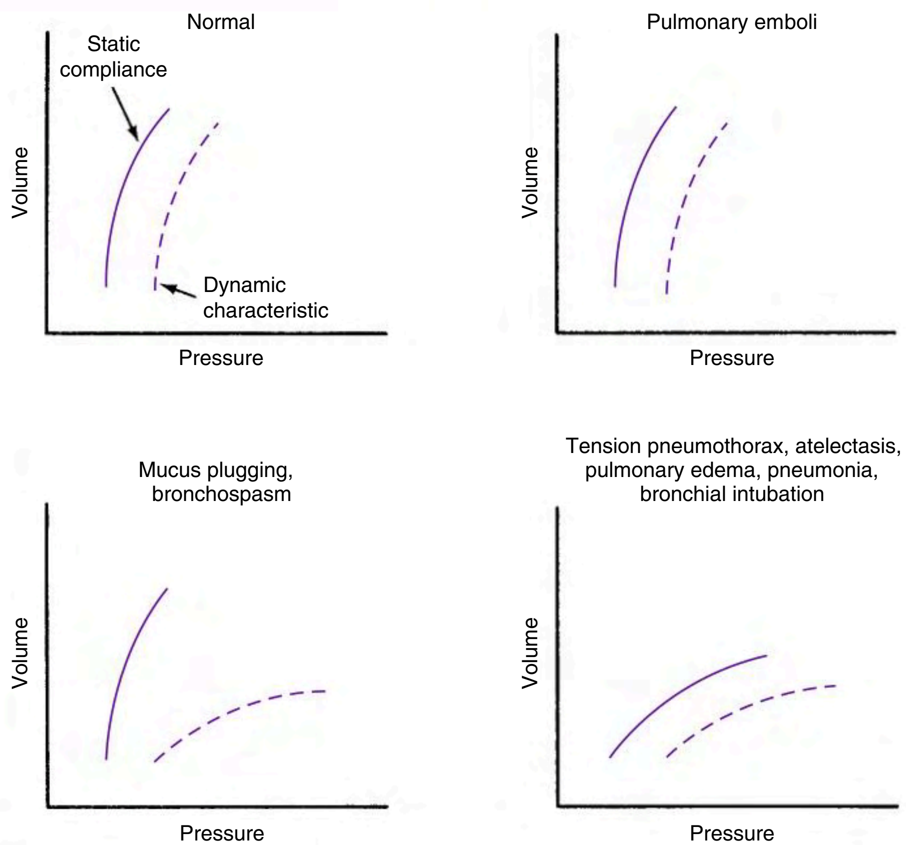


Fig. 8.13 Pressure-volume curves reflecting changes in C_S and C_D during mechanical ventilation. Under normal conditions, the C_S and C_D curves are similar. Because pulmonary emboli do not affect resistance or compliance, neither curve changes with this condition. With mucus plugging or bronchospasm, airway resistance increases, the C_D curve shifts to the right and flattens (more pressure is required), and the C_S curve remains unchanged. With conditions that reduce C_L, both curves shift to the right and flatten. (From Bone RC: Monitoring ventilatory mechanics in acute respiratory failure, *Respir Care* 28:597—603, 1983.)

emboli.[22-24] For example, conditions that affect the lung elasticity and airway resistance shift the dynamic compliance curve to the right and flatten it. If neither curve changes position but the patient develops hypoxemia, pulmonary embolus should be suspected. Table 8.3 correlates P-V curve data with clinical findings to aid evaluation of the patient's pulmonary condition.

Figs. 9.18 and 9.19 provide examples of C_D curves or P-V loops graphed by newer ventilators such as the Hamilton Galileo (Hamilton Medical, Bonaduz, Switzerland), CareFusion Avea (CareFusion Corp, San Diego, Calif.), Medtronics Puritan Bennett 840 and 980 (Medtronics Minimally Invasive Therapies), Dräger Evita XL (Dräger Medical, Inc., Telford, Pa.), and Servo-i (Maquet Inc, Wayne, N.J.) (Key Point 8.9).

Some ventilators, such as the Hamilton G5, can graph a slow dynamic P-V loop using slow flows and preset PEEP levels. A software program manages the maneuver and draws the resulting graph. Slow P-V loops may have value for establishing inflection points on the curve (see Chapter 13).

Fig. 8.14 shows a static P-V curve for a patient with normal lungs and a P-V curve for a patient with ARDS. Notice that the contour of the graph for the patient with ARDS has a sigmoid shape (S shape). The **lower inflection point** marks a significant change in the slope of the curve and may indicate the pressure at which large numbers of alveoli are recruited. The **upper inflection point** indicates a point at which large numbers of alveoli are becoming overinflated. Attempts should be made to provide ventilation to the patient between these two points.

Graphic displays of pressure-volume relationships have been shown to be useful in the treatment of patients with ARDS.[24-27] During the procedure for obtaining a P-V curve, the patient is typically heavily sedated and short-acting paralytic agents may be required. Lung inflation can be accomplished with the ventilator if it has the appropriate software. Alternatively, lung inflation can be accomplished with a super syringe (i.e., a 1—3 L syringe). With the syringe technique, a graduated, super syringe is attached to the ET (Fig. 8.15). Precise volumes of gas (e.g., 100—200 mL) are pushed into the lung and held for 2 seconds or long enough to allow measurement of P_{plat}. The pressure is measured after the delivery of each volume, and the P-V curve is then manually plotted by the respiratory therapist. It is worth mentioning that obtaining P-V measurements using the syringe technique is generally well tolerated by patients; however, the procedure can cause significant

BOX 8.11 Technique for Obtaining Pressure-Volume Curves

1. The patient is normally placed in the supine position, or the head of the bed is slightly elevated and the patient is relaxed. The person cannot be spontaneously breathing because the P_{plat} measurements will be inaccurate. (Use of sedation may be necessary.) Explain the procedure to the patient if appropriate.
2. Inflate the airway cuff to eliminate leaks; check the system for leaks and remove all of them.
3. Select the inspiratory pause control for each volume measurement.
4. Select a series of tidal volume (V_T, such as 6, 8, 10, 12, and 14 mL/kg or 250, 500, 750, 1000, and 1250 mL. Do not let P_{plat} become excessively high.)*
5. For each volume setting, record the peak inspiratory pressure (PIP), P_{plat}, end-expiratory pressure (EEP), and V_T. (Subtract EEP from PIP and P_{plat} before recording.)
6. Closely monitor the patient's hemodynamic status during the procedure.
7. Allow return to normal settings for several breaths between each test volume setting.
8. Remove the inspiratory pause.
9. Return cuff pressures to minimum leak or initial pressure or volume.
10. Perform a complete patient-ventilator system check.
11. Plot the data (see Fig. 8.14).

*If pressure rises rapidly and markedly, discontinue study to prevent lung injury.

Key Point 8.9 Dynamic P-V loops reflect changes in compliance during gas flow. Static P-V loops represent changes in compliance when no gas flow is present.

TABLE 8.3 Correlation of Pressure-Volume Curve Data and Clinical Findings to Evaluate Pulmonary Condition

Diagnosis	C_S	C_D	Chest Radiograph	P_aO_2	PAOP	Treatment
Pulmonary edema (cardiogenic)	↓	↓	↑ Vascular markings; possible heart size	↓	↑	Diuretics, digitalis, morphine, oxygen
ARDS	↓	↓	Diffuse infiltrate	↓	Normal	PEEP and supportive care
Pneumonia	↓	↓	Consolidation in affected area	↓	Normal	Antibiotics and supportive care
Atelectasis	↓	↓	Collapse of affected area	↓	Normal	Treat cause and give supportive care
Pneumothorax	↓	↓	No vascular markings in affected area	↓	Normal	Chest tube; chest drainage if severe
Bronchospasm	No change	↓	Possible hyperinflation	↓	Normal	Bronchodilator therapy

↓, decreased; ↑, increased; *ARDS,* acute respiratory distress syndrome; C_D, dynamic compliance; C_S, static compliance; P_aO_2, arterial oxygen partial pressure; *PAOP,* pulmonary artery occlusion pressure; *PEEP,* positive end-expiratory pressure.

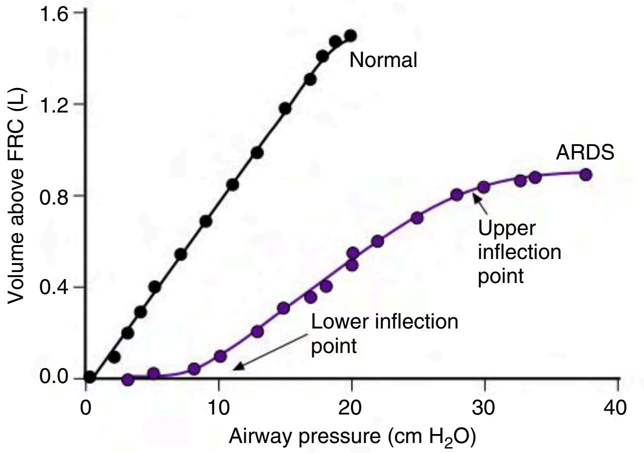


Fig. 8.14 Pressure-volume curves for normal lungs and the lungs of patients with acute respiratory distress syndrome (ARDS). Note the lower and upper inflection points on the pressure-volume curve for ARDS. *FRC,* Functional residual capacity. (From Hess DR, MacIntyre NR, Mishoe SC, et al.: *Respiratory care principles and practice,* Philadelphia, PA, 2002, WB Saunders.)

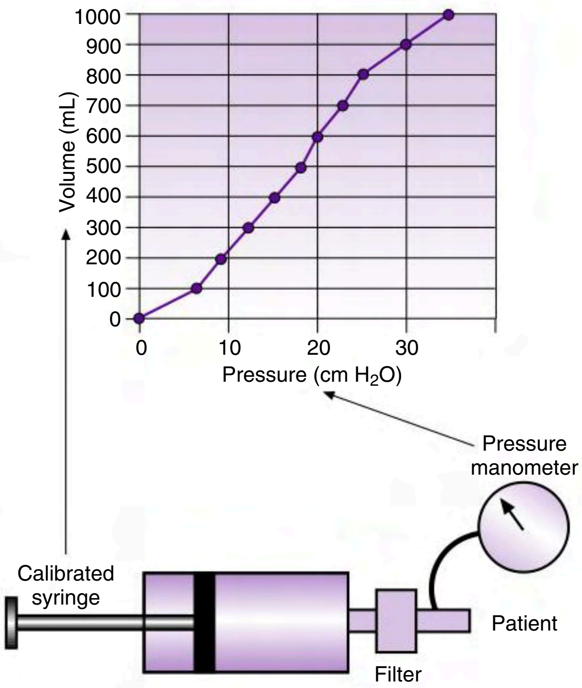


Fig. 8.15 Super syringe technique used to measure the pressure-volume (P-V) curve and an example of a P-V curve produced with this technique. (From Hess DR, MacIntyre NR, Mishoe SC, et al.: *Respiratory care principles and practice,* Philadelphia, PA, 2002, WB Saunders.)

changes in the patient's hemodynamic and oxygenation status. It is therefore prudent to closely monitor the patient during the procedure.[28]

Setting PEEP above the lower inflection point on the curve may help prevent inflated alveoli from collapsing and having to reexpand with each breath. Setting the V_T low enough so that PIP remains below the upper inflection point may reduce the risk for ventilator-induced lung injury. Assessment of the clinical data and analysis of the P-V curve can help the clinician establish the cause of a change in the patient's condition and determine the appropriate treatment.

Chapter 9 includes an overview of ventilator graphics along with examples of graphic displays typically encountered in ventilated patients. Additional information about the assessment of respiratory system mechanics is presented in Chapter 10. Chapter 13 provides details regarding specific procedures for obtaining and using P-V curves in the treatment of patients with ARDS.

COMMENT SECTION OF THE VENTILATOR FLOW SHEET

The patient-ventilator system check sheet includes a section for comments. The respiratory therapist can use this section to comment on any of the following:

- Patient assessment (e.g., breath sounds, chest wall movement, percussion note, presence of cyanosis, cutaneous perfusion, level of consciousness)
- Changes in ventilator settings
- Changes in the physician's orders
- Description of any equipment problems

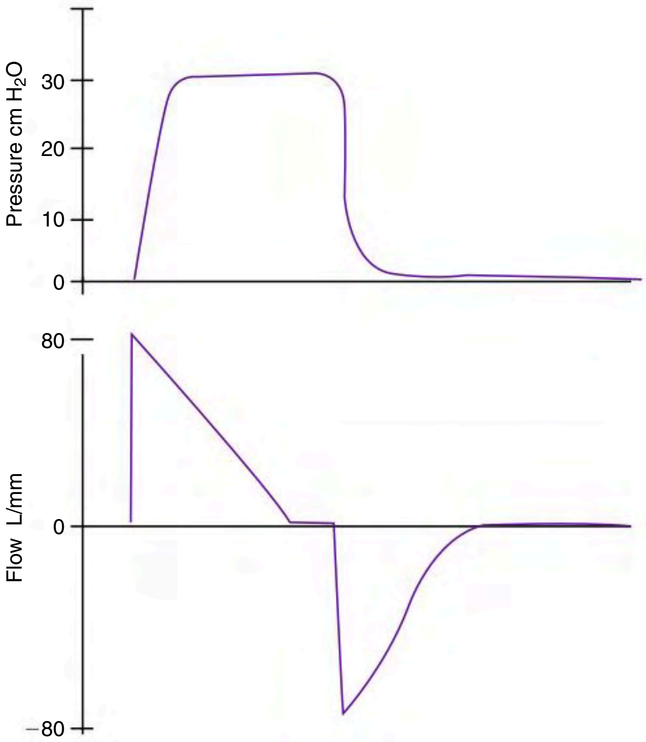
Some medical centers use a separate patient assessment sheet in which subjective findings, objective findings, the assessment, and the treatment plan (SOAP notes) can be summarized.

SUMMARY

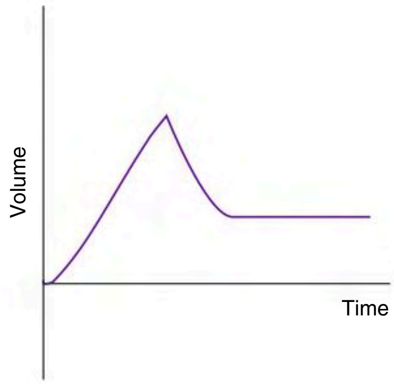
- Before connecting a patient to a mechanical ventilator, the respiratory therapist should verify that the designated ventilator has passed an operational verification procedure (OVP).
- The initial assessment of a patient receiving mechanical ventilation should include evaluation of the patient's physical appearance, vital signs, ABGs, S_pO_2, and ventilator settings (e.g., f, sensitivity, F_IO_2, volumes, pressures).
- The ventilator flow sheet is a necessary and valuable record of measured and observed patient and ventilator clinical values.
- Volumes, pressures, temperature, vital signs, and F_IO_2 are measured during each patient-ventilator system check.
- Initial assessment of the position of the ET and cuff pressure measurements establishes that the ET is positioned properly and cuff pressures have been set correctly.
- Calculation of V_D/V_T, compliance and resistance, and evaluation of P-V curves/loops help determine the baseline condition of the lung mechanics and can serve as a means to monitor changes.
- Evaluation of the integrity of the ventilator circuit is part of a standard ventilator check. It includes checking for leaks, disconnected tubing, and other circuit problems.
- Visual and auditory alarms are essential components of the patient-ventilator system.
- Computerized ventilator graphics included on most ICU ventilators have extended the clinician's ability to perform bedside assessment of the patient-ventilator interaction.

REVIEW QUESTIONS *(See Appendix A for answers.)*

1. Before a ventilator is used, an operational verification check is performed. A simple variation of this procedure is also performed under which of the following circumstances?
   A. Before a blood gas sample is obtained
   B. When the physician's order specifies a change in ventilator settings
   C. Before a patient is reconnected to a ventilator after the ventilator circuit has been changed or disassembled for any reason
   D. Before the patient's hemodynamic status is monitored
2. When should the F_IO_2 be measured with an oxygen analyzer?
   1. At least every 24 hours
   2. Continuously with infants
   3. During suctioning procedures
   4. When static P-V loops are determined
   5. 1 and 2 only
   6. 2 and 3 only
   7. 1 and 4 only
   8. 1, 2, 3, and 4
3. A patient has a P_{TA} of 5 cm H_2O. Three hours later a high-pressure alarm activates. The patient's P_{TA} is now 14 cm H_2O. What is the most likely cause of this change?
   A. Pneumothorax
   B. Deflated ET cuff
   C. Water in the circuit
   D. Secretions in the airway
4. A 36-year-old man with ARDS is receiving ventilation with a V_T of 400 mL. The patient's IBW is 176 lb (80 kg). The HME has a volume of 50 mL. What is an approximate alveolar volume for one breath for this patient?
   A. 350 mL
   B. 260 mL
   C. 270 mL
   D. 190 mL
5. The following figure shows pressure-time and flow-time curves obtained during PC-CMV. What is the P_{plat}?



   A. It cannot be determined from this graph.
   B. 30 cm H_2O
   C. 30 cm H_2O − Set PEEP
   D. 25 cm H_2O



6. Which of the following problems is illustrated in the previous figure?
   A. A leak in the patient-ventilator system
   B. Water in the inspiratory line
   C. A set inspiratory pause
   D. Active exhalation
7. A physical examination of the chest is performed on a mechanically ventilated patient. Breath sounds and percussion are normal except over the right middle lobe, where late inspiratory crackles are heard. This area is dull to percussion. A bedside chest radiograph reveals infiltrates in the right middle lobe. On the basis of these findings alone, which of the following is the most likely problem?
   A. Pneumothorax in the right hemithorax
   B. Congestive heart failure
   C. Right middle lobe pneumonia
   D. Asthma affecting the right side only
8. The following values are obtained from a patient's ventilator flow sheet:

Time	Volume (mL)	PIP (cm H_2O)	P_{plat} (cm H_2O)
01:00	850	36	33
02:00	850	39	32
03:00	850	43	33

9. Which of the following statements about these conditions is correct?
   C_L is improving.
   C_D has not changed.
   R_{aw} is improving.
   R_{aw} is getting worse.
10. A static P-V curve for C_S and C_D reveals a widening gap between the two curves. What does this probably represent?
11. A patient has an IBW of 150 lb, a V_T of 0.55 L, and an f of 8 breaths/min. What is the estimated alveolar ventilation?
12. While listening with a stethoscope over the trachea during VC-CMV, the respiratory therapist hears a slight leak at the end of inspiration in an orally intubated patient. What change should the therapist make?
   A. Increase cuff pressure until no sound is heard

B. Check cuff pressure and delivered volume
C. Check cuff volume
D. Recommend changing the artificial airway

13. A 6-ft, 4-in, 215-lb man has a size 7 oral ET in place. Cuff pressure is 35 mm Hg. The set V_T is 600 mL (0.6 L), and the delivered V_T is 500 mL (0.5 L). The patient is likely to need mechanical ventilation for at least a week. What would you recommend?
A. Increase the set V_T
B. Reduce the cuff pressure to 20 mm Hg
C. Change the ET to a size 8
D. Make no changes at this time

14. The following data were obtained for a patient on PC-CMV: What do you think is causing the change in V_T and what should the respiratory therapist evaluate?

Time	Set Pressure (cm H_2O)	V_T (mL)
21:00	20	550
23:00	20	575
01:00	20	620

15. A high-volume/low-pressure cuff has a pressure of 15 mm Hg as measured with a BP manometer technique. The respiratory therapist does not hear a leak when listening over the tracheal area with a stethoscope. What should the respiratory therapist do?
A. Reevaluate the cuff pressure because this technique is not trustworthy
B. Increase the cuff pressure to 20 to 25 mm Hg
C. Maintain the current pressure because this will augment tracheal perfusion
D. Be concerned about high cuff pressures damaging the airway

16. While changing the tape on the ET, the respiratory therapist accidentally cuts the pilot balloon line. This problem can be corrected by:
A. Using a stopcock, blunt-tipped needle, and syringe to reinflate the cuff and keep it inflated
B. Changing the ET
C. Clamping the pilot line with a hemostat
D. Increasing the flow on the ventilator

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CHAPTER 9

Ventilator Graphics

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OUTLINE

KEY TERMS

- Asynchrony
- Hysteresis
- Scalar

LEARNING OBJECTIVES

On completion of this chapter, the reader will be able to do the following:

1. Identify ventilator variables (e.g., target variable, trigger variable) and ventilator parameters and their values (e.g., peak inspiratory pressure, plateau pressure) using pressure, flow, and volume scalars generated with various modes of mechanical ventilation.
2. Identify ventilator variables and ventilator parameters and their values from flow-volume and pressure-volume loops.
3. Use ventilator scalars and loops to detect changes in lung compliance and airway resistance, inappropriate sensitivity settings, inadequate inspiratory flow, autopositive end-expiratory pressure (auto-PEEP), leaks in the ventilator circuit, active exhalation during pressure support ventilation, and an inspiratory pressure overshoot during pressure support ventilation.
4. Describe how changes in airway resistance and lung compliance affect scalars and loops during volume-targeted and pressure-targeted ventilation when airway resistance increases and lung compliance decreases.
5. Recognize periods of patient-ventilator asynchrony using scalars and loops.
6. Determine the presence of auto-PEEP using ventilator graphics.
7. Explain the phases of ventilation during airway pressure release ventilation using pressure and flow scalars.
8. Describe the relationship between airway and esophageal pressure changes using ventilator graphics.

Modern mechanical ventilators (e.g., Dräger v500 [Dräger Medical Inc., Telford, PA], CareFusion AVEA [CareFusion, Viasys Corp, San Diego, CA], Maquet Servo-i [Maquet Inc. Wayne, NJ], Puritan Bennett 840 [Covidien-Nellcor and Puritan Bennett, Boulder, CO], and Hamilton G5 [Hamilton Medical, Bonzduz, Switzerland]) incorporate graphic displays into their ventilator interfaces to provide instantaneous displays of pressure, flow, and volume. These graphic displays allow clinicians to obtain real-time measurements of the patient-ventilator interaction, which can provide insight into a patient's mechanics of breathing. Thus ventilator graphics offer valuable information for clinicians making adjustments to ventilator settings.[1-3]

Becoming proficient in the use of ventilator graphics typically requires dedicated time and practice. Once this skill is mastered, however, it can greatly enhance a clinician's ability to assess patient-ventilator interactions and improve patient care. Indeed, ventilator graphics can alert the clinician to abnormalities even before clinical signs are obvious and provide a graphic record of the pathophysiological changes that can lead to patient-ventilator **asynchrony** and respiratory distress.

Proprietary software programs offered by the ventilator manufacturers allow for flow, pressure, and volume measurements to be displayed as different types of waveforms. The term **scalar** is used to specify the flow, pressure, and volume waveforms that are graphed relative to time (i.e., pressure, flow, and volume scalars).[5] Basically, six shapes (waveforms) are produced with scalars during mechanical ventilation (Fig. 9.1 and Box 9.1)[4-6] The term *loop* is used to describe a graph of two variables plotted on the *x* and *y* coordinates, such as pressure-volume and flow-volume loops (these are discussed later in the chapter).

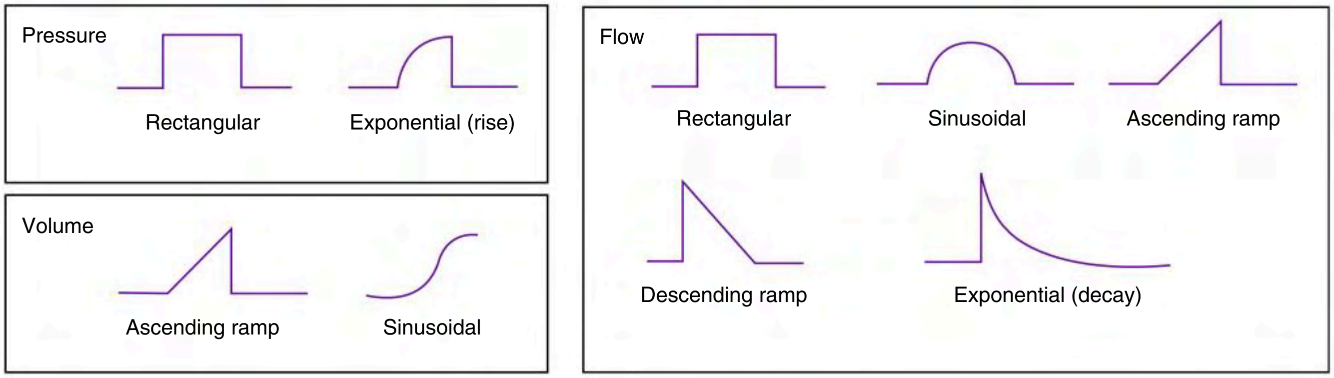

Fig. 9.1 Examples of waveforms for pressure, volume, and flow. Pressure waveforms are usually the rectangular or rising exponential *(similar to an ascending ramp)* type. Volume waveforms are usually the ascending ramp or sinusoidal type. Flow waveforms can take various forms; the rectangular, ramp *(ascending or descending)*, sinusoidal, and decaying exponential waveforms are seen most often.

BOX 9.1 Six Basic Curves (Waveforms)

Rectangular (often called the square wave or constant waveform)
Descending ramp (also called a decelerating ramp)
Ascending ramp (also called an accelerating ramp)
Sinusoidal (often called the sine wave; only half or part of this wave is present)
Rising exponential
Decaying exponential

RELATIONSHIP OF FLOW, PRESSURE, VOLUME, AND TIME

Flow, pressure, volume, and time must be determined to produce the various waveforms and loops. The following principles explain the basic interrelationship of volume, pressure, flow, and time as they are used to create a waveform display:

1. The flow of gas into the lungs depends on the difference between the pressure from the power source (the ventilator) and the pressure inside the lungs. The greater the pressure gradient, the higher is the flow of gas, and the faster the lungs fill. Flow is measured as a volume change per unit of time, where time is the inspiratory time (Flow $= V/T_I$).
2. The amount of pressure (ΔP) required to inflate the lungs depends on the patient's lung compliance and airway resistance. If the lungs are compliant and easy to inflate, relatively low pressures are required. If the lungs are stiff (low compliance), considerably higher pressures are required to inflate them ($\Delta P = \Delta V/C_L$). For airway resistance, the most important factor affecting the degree of resistance is the diameter of the airways (or more specifically the radius according to Poiseuille's law). Airway resistance decreases as the diameter of the airway increases, resulting in an increased flow. Conversely, airway resistance increases as the diameter of the airway is reduced, causing a decreased flow (Key Point 9.1). Note that the ventilator's microprocessor can calculate both compliance and resistance using the measured data.

Key Point 9.1 The amount of pressure (ΔP) required to inflate the lungs depends on the patient's lung compliance and airway resistance.

3. The volume (V) delivered depends on the amount of flow and inspiratory time (T_I) ($V = \text{Flow} \times T_I$).

A CLOSER LOOK AT SCALARS, CURVES, AND LOOPS

Scalars

Fig. 9.2 shows a typical set of scalars for volume-controlled continuous mandatory ventilation (VC-CMV). Note the directional arrows indicating the movement of flow into the lungs and the corresponding rise in airway pressure and resulting delivered volume. Also, notice that flow rises to its peak value and remains constant throughout inspiration.

Fig. 9.3 presents a closer look at a flow scalar. At point *A*, the inspiratory valve opens, allowing gas flow into the lungs. Keep in mind that this is also the point at which expiration ends. Flow rises quickly to point *B*, which is the peak inspiratory flow set on the control panel of the ventilator. What is the inspiratory flow setting in this example? At point *C*, inspiratory flow delivery stops. Has an inspiratory pause been set on the ventilator? What is the length of T_I? What is the flow during the pause period?

In this example, as the expiratory valve opens at point *D*, gas leaves the patient and the ventilator circuit and passes through the ventilator's expiratory valve. Flow during exhalation is graphed below the baseline, as specified by the software program. Look at the expiratory flow curve. What is the peak expiratory flow rate (PEFR)?*

Continue to follow the expiratory flow curve. Note that at point *E*, expiratory flow ends; however, the total expiratory time (T_E) lasts from point *D* to point *F*, and the T_E continues until the next

*PEFR is 80 L/min. (Even though the graph indicates minus [−] 80 L/min, the value is read without the minus sign.)

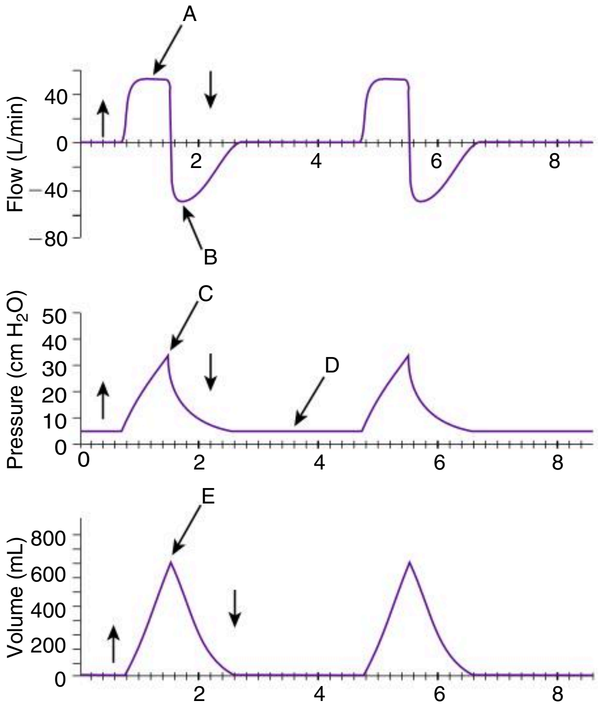

Fig. 9.2 Time-triggered, constant-flow, volume-targeted ventilation (VC-CMV). (A) Peak inspiratory flow; (B) peak expiratory flow; (C) peak inspiratory pressure; (D) baseline pressure; (E) delivered inspiratory tidal volume. (Modified from Hess DR, MacIntyre NR, Mishoe SC, et al.: *Respiratory care principles and practice,* Philadelphia, PA, 2002, WB Saunders.)

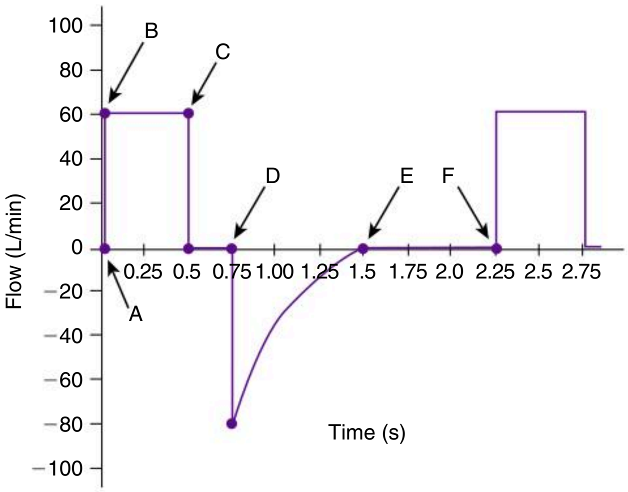

Fig. 9.3 Flow-time graph showing inspiration and expiration during volume ventilation with a constant flow. (See text for explanation.)

inspiration begins (point *F*). How long is the T_E? How much of the T_E is represented by a period of no gas flow?[†]

Fig. 9.4 shows a VC-CMV breath, but notice that the flow pattern has been set to decelerating pattern. Can you explain why this would not be representative of a pressure-controlled continuous mandatory ventilation (PC-CMV) breath? (Hint: Look at the contour of the pressure scalar.)

[†] T_E = 1.5 seconds. 1.5 to 2.25 seconds (0.75-second total) is the interval during exhalation when no more gas leaves the patient.

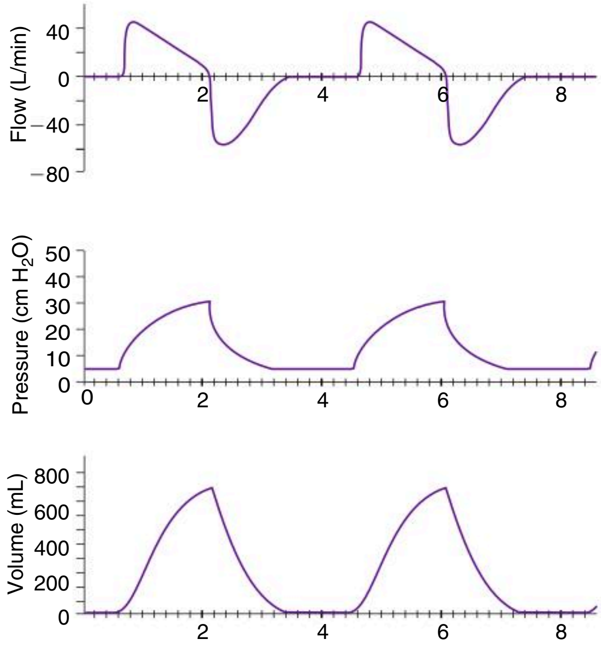

Fig. 9.4 Time-triggered, descending-flow, volume-targeted ventilation (VC-CMV). (Modified from Hess DR, MacIntyre NR, Mishoe SC, et al.: *Respiratory care principles and practice,* Philadelphia, PA, 2002, Saunders.)

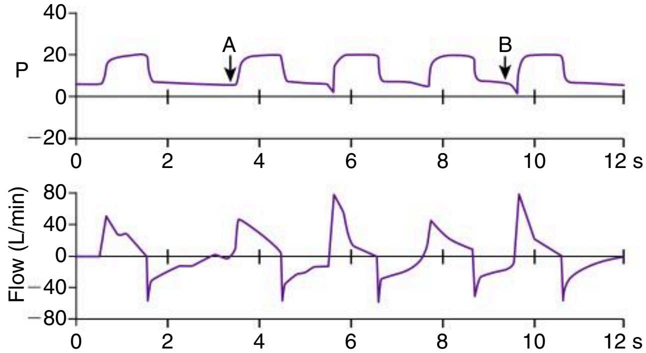

Fig. 9.5 Pressure and flow scalars for time-triggered (A) and patient-triggered (B) breaths.

Scalars also can be used to identify how a ventilator breath is initiated (i.e., time triggered or patient triggered). In Fig. 9.5 arrow *A* indicates a time-triggered breath and arrow *B* shows a patient-triggered breath. Notice that for breath B there is a slight drop in baseline pressure, indicating a patient effort. Can you determine whether this is a PC or VC breath? (Hint: Look at the flow scalar.) Additional information about PC versus VC breaths is presented in the following section on the comparison of pressure-controlled ventilation and volume-controlled ventilation.

As described in Chapter 5, intermittent mandatory ventilation (IMV) is a mode of ventilation that allows spontaneous breaths interspersed with mandatory breaths. Fig. 9.6 shows an example of a VC-IMV breath. Notice the minimal rise in pressure and tidal volume (V_T) for each spontaneous breath and the contour

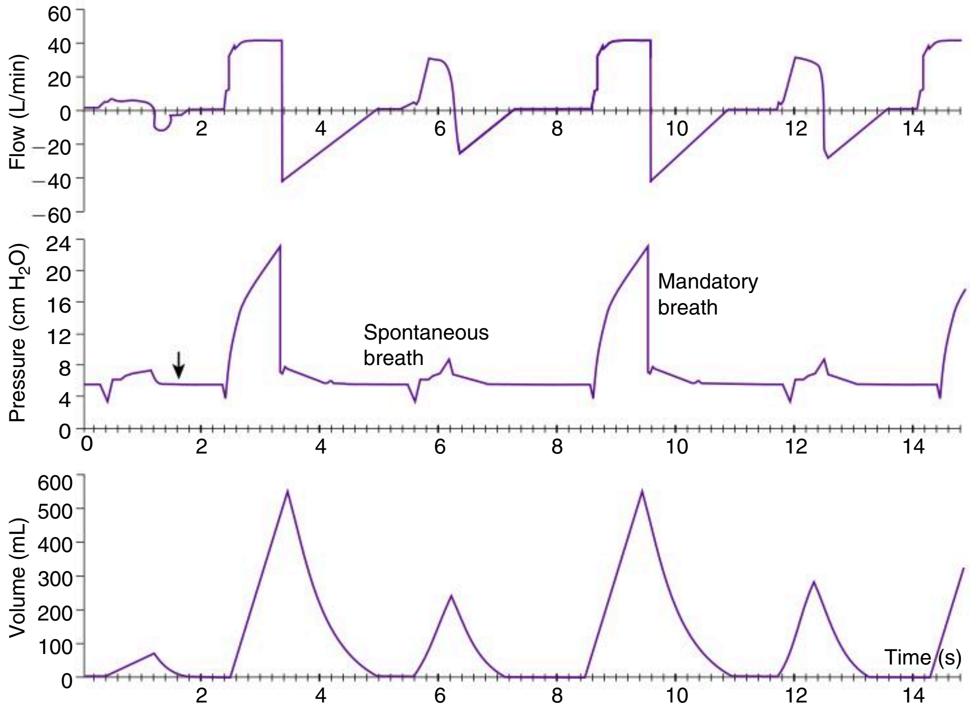

Fig. 9.6 Volume-controlled intermittent mandatory ventilation (VC-IMV) plus continuous positive airway pressure/positive end-expiratory pressure (CPAP)/PEEP. (See text for explanation.) (From Hess DR, MacIntyre NR, Mishoe SC, et al.: *Respiratory care principles and practice,* Philadelphia, PA, 2002, WB Saunders.)

difference in flow, pressure, and volume between the mandatory and spontaneous breaths. The elevated baseline pressure (see the *arrow* on the pressure scalar) indicates that the patient is receiving positive end-expiratory pressure (PEEP).

During PC-CMV, the flow and pressure patterns differ from those of VC-CMV breaths. As shown in Fig. 9.7, the flow pattern for PC-CMV is decelerating with a constant *(square)* pressure pattern. PC-CMV breaths always generate a decelerating flow pattern, whereas the flow pattern for VC-CMV can be changed from square to decelerating. Notice also the change in peak flow that occurs with changes in patient demand during PC-CMV *(dashed line)*.

Mandatory pressure-targeted breaths can also be delivered with PC-IMV as shown in Fig. 9.8. Compare the difference in the flow and pressure scalars for the mandatory breaths and spontaneous breaths in this graphic with those in Fig. 9.6. The spontaneous breaths have a flow and pressure pattern typically associated with a pressure-targeted breath and are representative of a pressure support breath.

Comparison of Pressure-Controlled Ventilation and Volume-Controlled Ventilation

When pressure and volume breaths are compared, the pressure and flow curves demonstrate the most distinct differences. Volume-controlled ventilation with constant flow produces a rectangular flow curve, which can be changed by selecting a different flow waveform.

During pressure-controlled ventilation, the flow waveform is a descending curve that varies with both lung characteristics and patient flow demand; therefore it is referred to as a *continuously variable decelerating waveform* (Key Point 9.2).

***Key Point* 9.2** Volume-controlled ventilation with constant flow produces a rectangular flow curve, which can be changed by selecting a different flow waveform. During pressure-controlled ventilation the flow waveform is a descending curve that varies with both lung characteristics and patient flow demand.

During volume-controlled ventilation, the pressure scalar resembles an ascending ramp, or a *rising exponential curve.* During pressure-controlled ventilation, it is rectangular, assuming T_I is long enough. (See the section on monitoring pulmonary mechanics for additional information.)

Determining the Mode of Ventilation

Scalars can also be used to identify the mode of ventilation being used. By carefully examining the pressure and flow scalars, it is possible to determine whether mandatory, spontaneous, or IMV is being used. Fig. 9.9 illustrates the flow, pressure, and volume scalars for mandatory and spontaneous breaths during IMV. Fig. 9.10 also demonstrates flow, pressure, and volume scalars during IMV; however, careful examination of the spontaneous breaths shows that the spontaneous breaths are not being pressure supported. (Case Study 9.1 provides an example illustrating how ventilator graphics can be used to identify the mode of ventilation being used.)

Components of the Pressure-Volume Loop

Pressure-volume (P-V) loops can be used to monitor changes in lung compliance ($C_L = \Delta V/\Delta P$) and airway resistance. Fig. 9.11 shows a typical P-V loop generated during a positive pressure

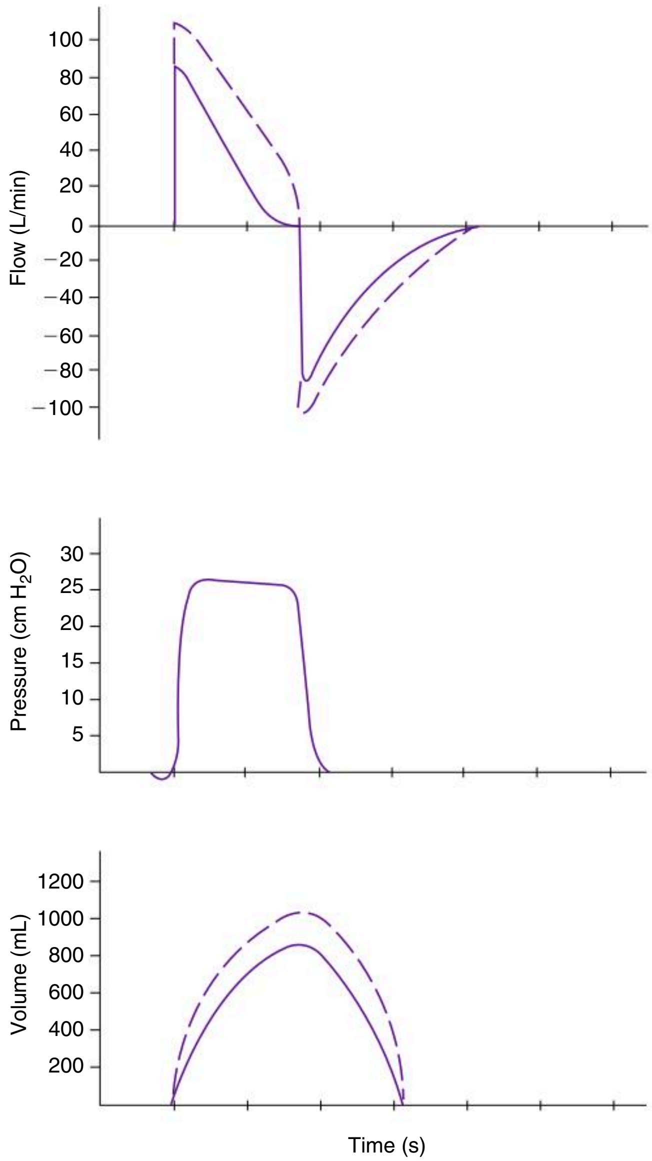

Fig. 9.7 Flow, pressure, and volume. Scalars seen during pressure-controlled continuous mandatory ventilation (PC-CMV).

breath. This breath is time triggered by the ventilator rather than patient triggered. It is important to recognize that the P-V loop is drawn in a counterclockwise direction when a ventilator breath is delivered. Notice also that the inspiratory and expiratory curves are not perfect arcs. The maximum pressure shown on the *x* axis is the peak inspiratory pressure (PIP), and the maximum volume reached on the *y* axis is the V_T.

Fig. 9.12 provides additional information regarding pressure gradients that can be determined using a P-V loop. The *solid line* of the loop in Fig. 9.13 represents pressure at the airway opening (P_{awo}) during a V_T. The *dashed line* represents the static P-V line, which reflects the alveolar pressure (P_{alv}) under no-flow conditions. The transairway pressure (P_{TA}), or flow-resistive pressure, is the difference between the P_{alv} and P_{awo}. P_{TA} is represented by a *double-headed arrow* in this figure. Try to determine the values for PIP, V_T, P_{TA}, and peak P_{alv} for the P-V loop shown in Fig. 9.12.

Case Study 9.1

A patient is switched from PC-CMV to PC-IMV to promote respiratory muscle activity. Initially the patient does not exhibit a spontaneous breathing frequency, but spontaneous efforts are subsequently noted on pressure and flow scalars. Describe how you would differentiate patient-triggered breaths and time-triggered breaths. (Hint: What type of breaths are the arrows indicating?)

Spontaneous Breaths and Pressure-Volume Loops

The clinician can learn to distinguish mandatory breaths from spontaneous breaths by observing the way the P-V loop is generated during breath delivery. When a patient makes a spontaneous inspiration, the P-V loop tracks in a clockwise fashion (Fig. 9.13). This is the reverse of a positive pressure breath, which creates a counterclockwise tracing (as shown in Fig. 9.11).

Now look at Fig. 9.14, which shows the P-V loop for a patient-triggered mandatory breath. When the patient breathes in spontaneously, the curve moves to the left *(clockwise),* reflecting the patient's effort. As the positive pressure from the ventilator is triggered, the curve crosses to the right and is traced in a counterclockwise fashion, which indicates that the machine is doing the work.

Components of the Flow-Volume Loop

Fig. 9.15 illustrates a typical flow-volume (F-V) loop recorded during a positive pressure breath. Inspiratory flow appears above the baseline, and expiratory flow is below the baseline. (NOTE: This is the reverse of the way F-V loops are usually reported for spirometry obtained during a standard laboratory pulmonary function test.) PEFR is the highest value on the expiratory flow curve. What is the PEFR in Fig. 9.15? What type of flow waveform is the ventilator delivering? What is the set inspiratory flow?[*]

Summary: Normal Scalars, Loops, and Curves

With the diagnostic use of scalars, P-V, and F-V loops, several key points should be reiterated:

- Scalars can be used to identify the phases and characteristics of mechanical ventilatory breaths including PIP, PEEP, peak flow,

[*] PEFR is approximately 70 L per minute (LPM), flow pattern is square, and inspiratory flow is approximately 55 LPM.

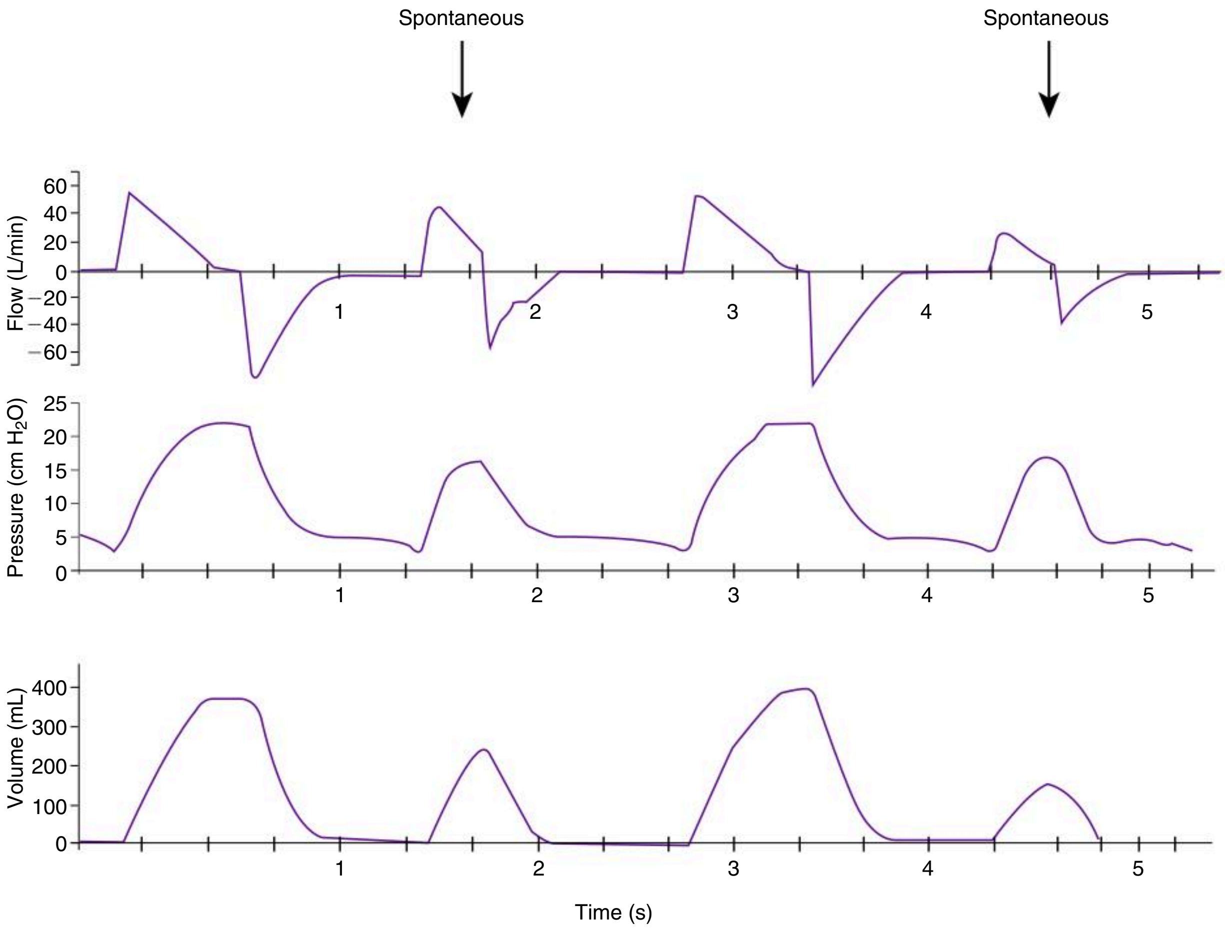

Fig. 9.8 Pressure, flow, and volume scalars for pressure-controlled intermittent mandatory ventilation (PC-IMV) plus pressure support and continuous positive airway pressure (CPAP). *Arrows* indicate spontaneous breaths. (See text for further information.)

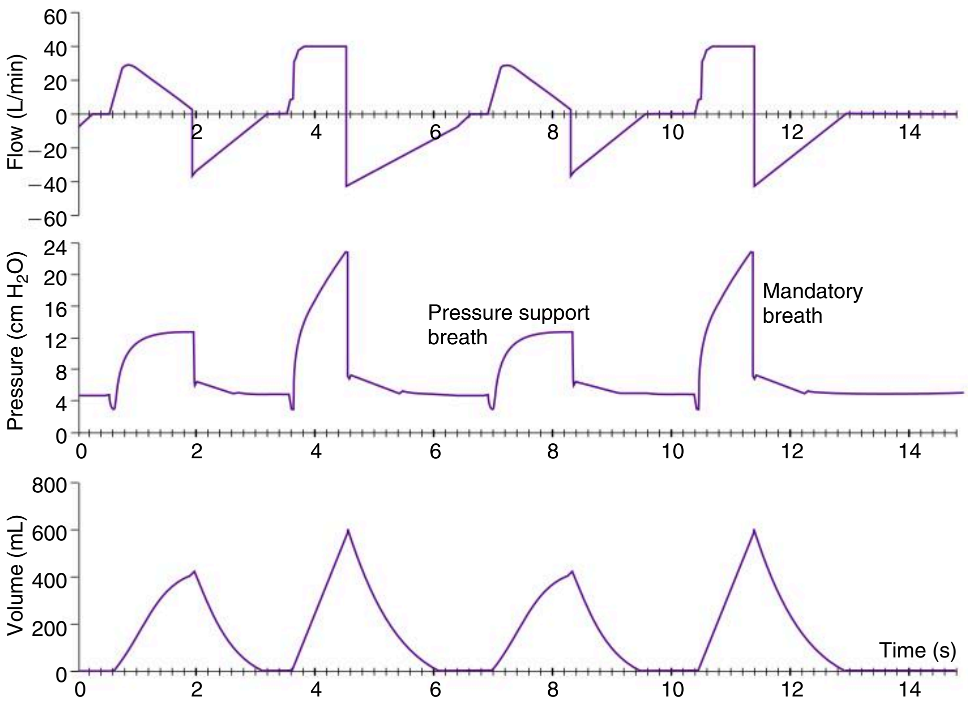

Fig. 9.9 Flow *(top),* pressure *(middle),* and volume *(bottom)* scalars during volume-controlled intermittent mandatory ventilation (VC-IMV) with pressure support ventilation (PSV) and continuous positive airway pressure (CPAP). (From Hess DR, MacIntyre NR, Mishoe SC, et al.: *Respiratory care principles and practice,* Philadelphia, PA, 2002, WB Saunders.)

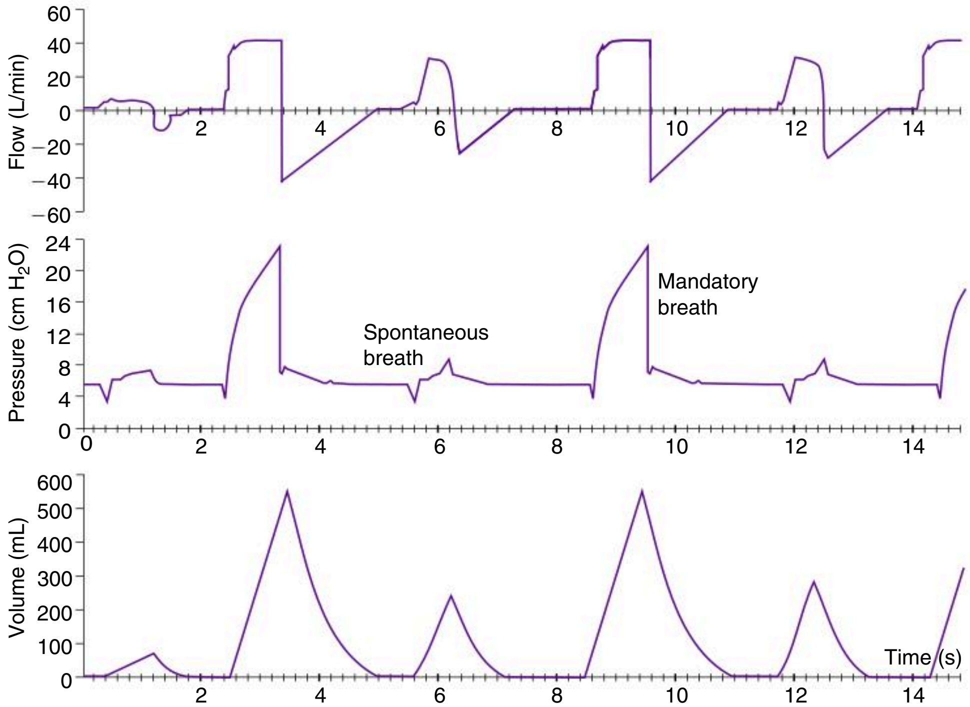

Fig. 9.10 Flow *(top)*, pressure *(middle)*, and volume *(bottom)* scalars during volume-controlled intermittent mandatory ventilation (VC-IMV) plus continuous positive airway pressure/positive end-expiratory pressure (CPAP/PEEP). (See text for explanation.) (From Hess DR, MacIntyre NR, Mishoe SC, et al.: *Respiratory care principles and practice,* Philadelphia, PA, 2002, WB Saunders.)

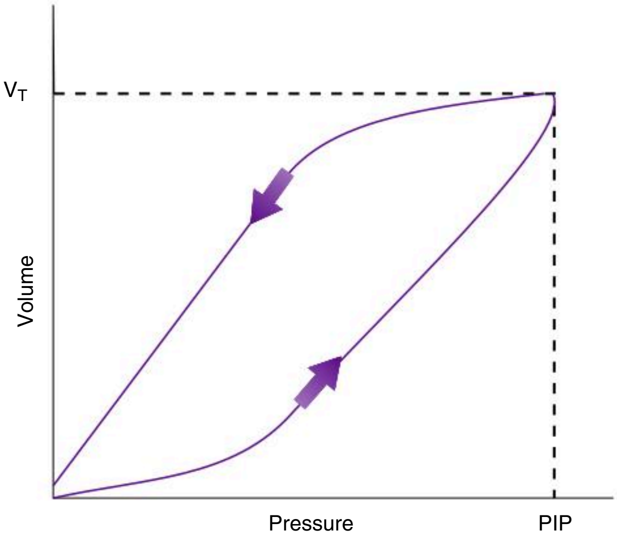

Fig. 9.11 Typical pressure-volume loop for a positive pressure breath. The loop represents the pressure and volume measured at the upper airway opening (P_{awo}). The highest point for tidal volume (V_T *[y axis]*) and peak inspiratory pressure (PIP *[x axis]*) represents the dynamic compliance for that pressure-volume relationship.

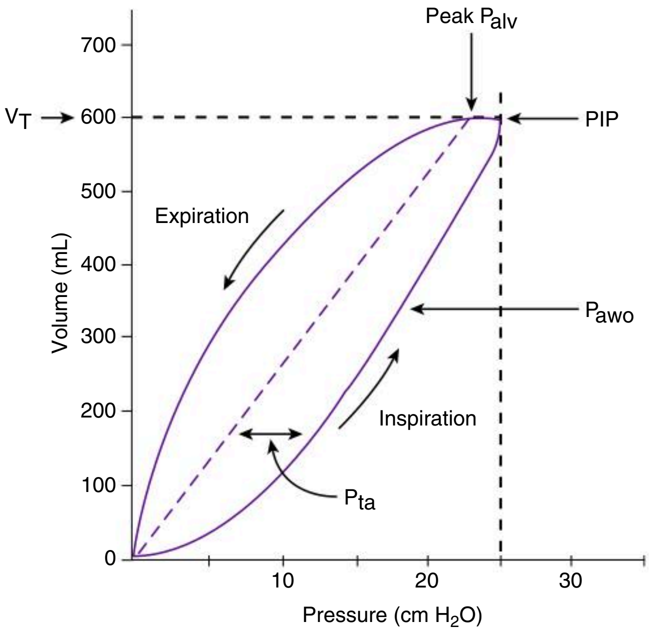

Fig. 9.12 P-V loop showing the peak inspiratory pressure (PIP), pressure at the airway opening (P_{awo}), alveolar pressure (P_{alv}), and transairway pressure (P_{TA}). (See text for additional information.)

expiratory flow, and patient-triggered and time-triggered breaths.

- The contour of the flow pattern identifies the type of preset flow for volume-controlled breaths and when viewed with the pressure pattern, volume-controlled breaths can be differentiated from pressure-controlled breaths.

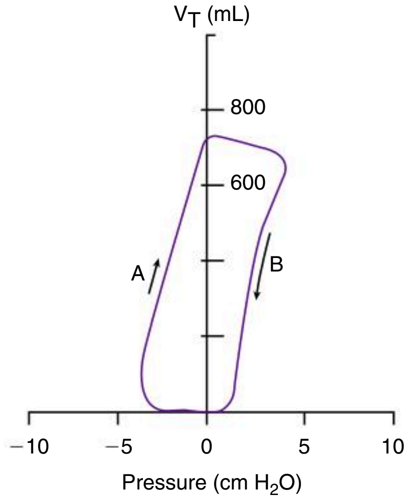

Fig. 9.13 Pressure-volume loop recorded during a spontaneous, unsupported breath. No continuous positive airway pressure (CPAP) or pressure support ventilation (PSV) is delivered. *Arrow A* indicates inspiration, and *arrow B* indicates expiration. (Modified from Puritan Bennett: *Waveforms: the graphical presentation of ventilator data, form AA-1594 [2/91]*, Pleasanton, CA, 1991, Puritan Bennett Tyco.)

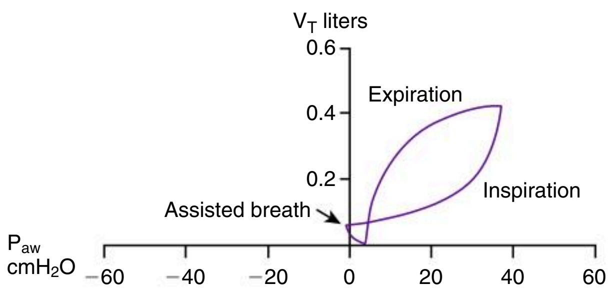

Fig. 9.14 Pressure-volume loop for a patient-triggered breath during pressure-controlled continuous mandatory ventilation (PC-CMV). Notice that part of the curve moves to the left of the *y* axis, reflecting a drop in pressure during inspiration (pressure value becomes negative); the curve traces to the right of the *y* axis as the ventilator delivers a positive pressure breath (pressure value becomes positive).

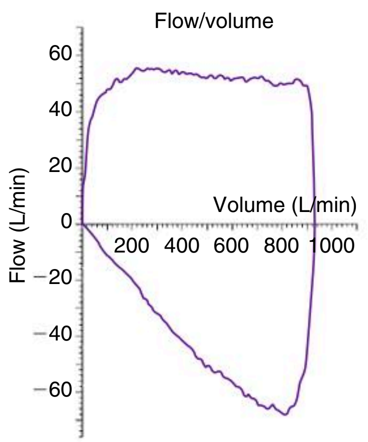

Fig. 9.15 Normal F-V loop during volume-controlled ventilation. The inspiratory curve is on the top, and the expiratory curve is on the bottom. Note the linear change in expiratory flow from peak to end expiration. Also, the end-expiratory flow is zero. (From Kacmarek RM, Hess D, Stoller JK: *Monitoring in respiratory care*, St. Louis, MO, 1993, Mosby.)

- In addition to identifying the breath type, scalars are useful in identifying the mode of ventilation.
- P-V curves can be an effective method to monitor pulmonary compliance and airway resistance.
- F-V loops can be a useful way to show the PEFR and inspiratory flow.

USING GRAPHICS TO MONITOR PULMONARY MECHANICS

Most intensive care unit (ICU) ventilators have the capability of measuring and displaying digital calculations of pulmonary compliance and airway resistance. Fig. 9.16 illustrates the flow, pressure, and volume scalars obtained during an inspiratory pause with a patient on VC-CMV.

Look first at the inspiratory portion of the pressure-time curve. Notice that the baseline pressure is 5 cm H_2O, indicating that 5 cm H_2O of PEEP is being used. (It is important to recognize that although the baseline pressure is positive, the flow and volume curves start from a zero baseline and end at a zero baseline.) Now observe the flow scalar during the inspiratory pause. Compare the flow and volume scalars at the same moment in time. Notice that when no flow occurs, there is no volume delivery. The volume curve also looks as if it has a pause, or plateau (Key Point 9.3).

P-V loops can be used to assess changes in pulmonary mechanics. In Fig. 9.17, line *AB* (peak P_{alv}) represents the pressure-volume relationship of the normal lung under static *(no-flow)* conditions; that is, it is the P_{alv} during static conditions. *C* represents the elastic component of the lungs and chest wall (see Fig. 9.17). Triangle *ABE* represents the amount of mechanical work required to overcome the elastic resistance of the lungs and

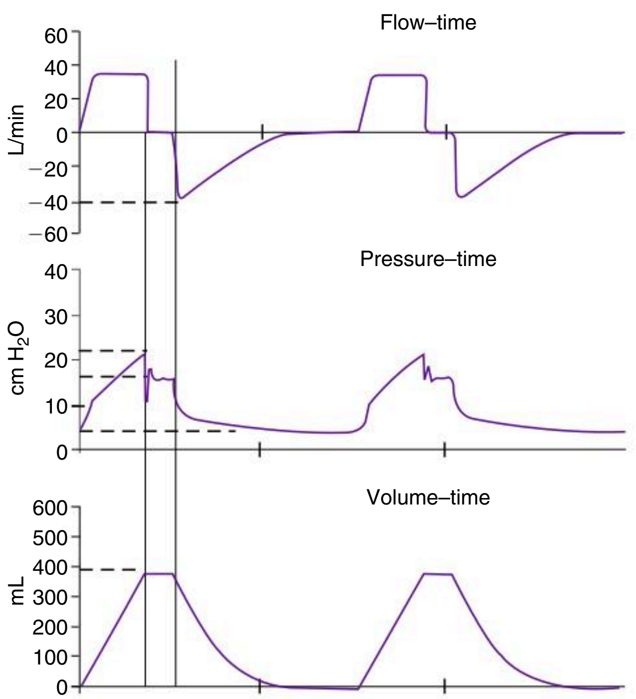

Fig. 9.16 Flow, pressure, and volume scalars during volume-controlled continuous mandatory ventilation (VC-CMV) with constant flow and an inspiratory pause. (See text for explanation.)

Key Point 9.3 When flow drops to zero at the end of inspiration, an inspiratory pause is present. When flow is zero, the pressure gradient between the ventilator and the patient's lungs is the same.

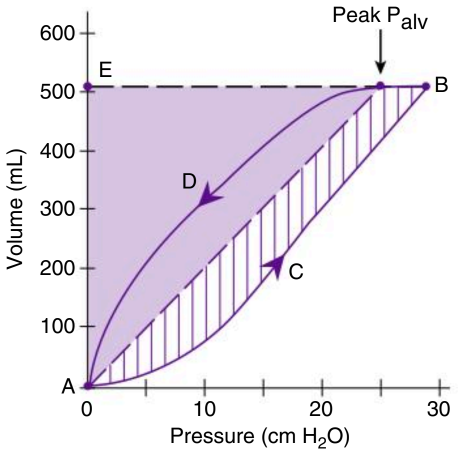

Fig. 9.17 P-V loop for a normal lung. Line *AB* represents compliance or the pressure-volume relation of the lung under static (no flow) conditions. Curve *ACB* is inspiration. Curve *BDA* is expiration. *Blue shaded area ABE* denotes work to overcome the elastic resistance of the lungs alone. *Cross-hatched area ACB* represents work performed to overcome nonelastic airflow resistance during inspiration. Area *ABD* represents airflow resistance during exhalation. The sum of the latter two areas represents the resistive work of breathing in one breath. Note that work is not performed during a normal exhalation. P_A, Alveolar pressure. (Modified from Dupuis Y: *Ventilators: theory and clinical application,* ed 2, St. Louis, MO, 1992, Mosby.)

chest wall. For a given amount of pressure applied to the lungs, a certain volume results. When flow is present, the direct *(straight-line)* relationship no longer exists; rather, as seen in previous P-V loops, the line curves during inspiration and expiration.

A certain amount of pressure is required during inhalation (see curve *ACB* in Fig. 9.17 and exhalation (curve *BDA*) to overcome the resistance of the airways and the tissues. These curves represent the nonelastic *(frictional)* forces opposing ventilation. Force *(pressure)* is applied to the lung by the action of the ventilator, but a slight lag time elapses before the volume actually increases. The area between curves *ACB (the inspiratory curve)* and *ADB (the expiratory curve)* is the result of **hysteresis** (Box 9.2). For any given lung volume, the elastic recoil in the lungs is less during exhalation than during inhalation.

The total mechanical work of breathing (WOB) is the sum of triangle *ABE* and curve *ACB*. Recall from physics that work equals force times distance. (In respiratory physiology, force is expressed as pressure and distance is expressed as volume.) In the lungs this translates to WOB, which approximately equals the pressure required to ventilate the lungs times the volume the lungs accumulate (WOB = P × V). The inspiratory work resulting from airway resistance (R_{aw}) and partly from tissue resistance is curve *ACB*. The expiratory work is represented by curve *ADB*. Chapter 10 provides more information on the monitoring of WOB; it also reviews the pressure-time product and the use of transdiaphragmatic pressure monitoring as a technique for estimating WOB.[24]

During positive pressure ventilation for less compliant (stiffer) lungs, greater pressure is required to achieve a given volume. The P-V loop therefore tends to flatten (Fig. 9.18).[25] Examples of lung conditions demonstrating reduced compliance include fibrotic diseases of the lung and conditions that flood the alveoli with fluids (e.g., pulmonary edema, pneumonia, and acute respiratory distress syndrome [ARDS]). Reduced compliance is also seen in conditions in which the alveoli are deflated (e.g., atelectasis). It is important to understand that as compliance decreases, airway pressure increases, but volume delivery remains constant during volume-targeted ventilation.

Compared with volume-targeted ventilation, lung volume decreases, whereas pressure remains at the preset level during a pressure-targeted breath as compliance changes (Fig. 9.19).

Pressure-volume curves can also reflect changes in airway resistance. Notice in the P-V curve in Fig. 9.17, the *dashed line* dividing the curve into an inspiratory and expiratory component. The width of each component reflects the resistive forces during the respective phase of ventilation. Now compare the width of the P-V curve shown in Fig. 9.20 with that of a P-V curve with normal resistance (see Fig. 9.17). Note how the width of the curve increases but the compliance *(slope of the isoflow line)* remains normal.

Flow-volume loops are routinely used in a pulmonary function laboratory to assess changes in airway resistance. Fig. 9.21 illustrates one of the most valuable uses of the F-V loop, evaluating R_{aw}. Loop *A* in Fig. 9.21 reflects normal R_{aw} during volume

BOX 9.2 Hysteresis

Hysteresis can be thought of as a lagging of one of two associated phenomena; that is, two associated phenomena fail to coincide or occur simultaneously. An example of hysteresis is the difference between the inspiratory and expiratory curves in a pressure-volume loop for the lungs, as shown in Fig. 9.12.

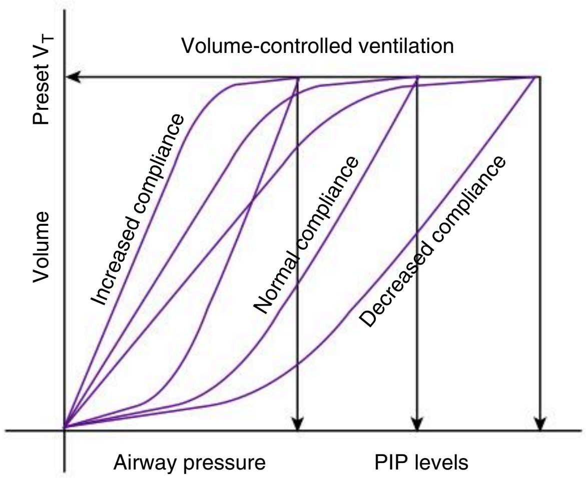

Fig. 9.18 Changes in the P-V loop during volume-targeted ventilation as lung compliance changes. Volume delivery remains constant, but peak inspiratory pressure (PIP) changes. (From Dhand R: Ventilator graphics and respiratory mechanics in the patient with obstructive lung disease, *Respir Care* 50:246—261, 2005.)

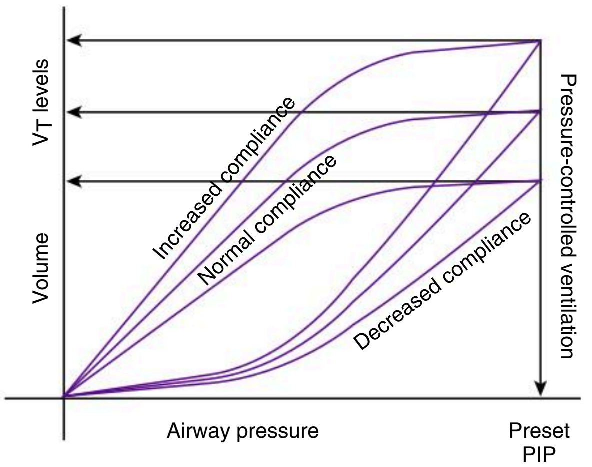

Fig. 9.19 P-V loops during pressure ventilation. As compliance changes, volume delivery changes, but pressure delivery remains constant. (From Dhand R: Ventilator graphics and respiratory mechanics in the patient with obstructive lung disease, *Respir Care* 2005;50:246–261.)

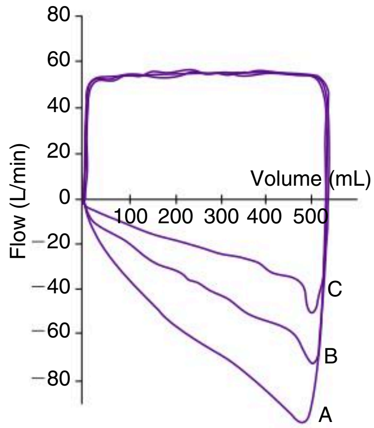

Fig. 9.21 F-V loops showing volume-targeted breaths with a constant flow but changing airway resistance *(compliance constant)*. Loop *A* shows a normal R_{aw}. Loops *B* and *C* represent progressively increasing R_{aw}. Note the drop in expiratory flow and peak expiratory flow rate (PEFR) as airway resistance increases.

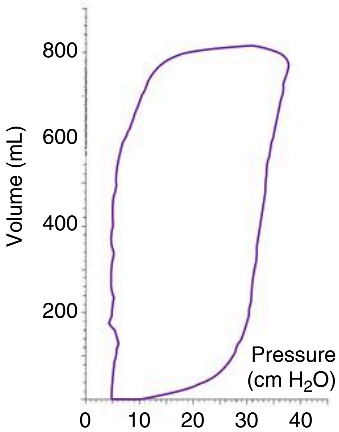

Fig. 9.20 Airway P-V loop recorded in a patient with chronic obstructive pulmonary disease (COPD) during controlled ventilation. Note the increased nonelastic inspiratory and expiratory work *(widening of the loop)* and the shift of the dynamic compliance curve *(P-V loop)* upward and to the left. *PIP,* Peak inspiratory pressure. (From Kacmarek RM, Hess D, Stoller JK: *Monitoring in respiratory care,* St. Louis, MO, 1993, Mosby.)

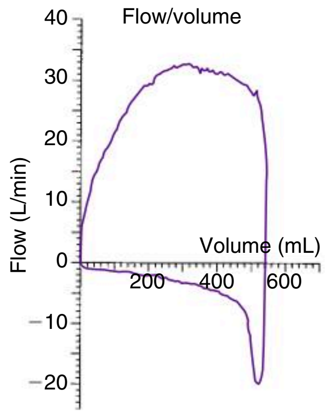

Fig. 9.22 F-V loop during volume ventilation in a patient with chronic obstructive pulmonary disease (COPD). Note the diminished peak expiratory flow and the scooped-out *(concave)* shape of the expiratory F-V curve. (NOTE: The flow scale is 0 to 30 L/min during inspiration and 0 to −20 L/min during exhalation.) The clinician must make sure to check the scale when reading graphs. Inspiration *(top)* and expiration *(bottom)*. (From Kacmarek RM, Hess D, Stoller JK: *Monitoring in respiratory care,* St. Louis, MO, 1993, Mosby.)

ventilation with a constant flow and a normal compliance. Loops *B* and *C* show the effects of increasing R_{aw}. The inspiratory F-V curve is not significantly affected because the ventilator is set to deliver a constant flow (50 L/min) and volume (about 530 mL). However, PEFR progressively decreases as R_{aw} increases.

A reduction in PEFR is most often associated with airway obstruction (e.g., secretions and bronchospasm). Fig. 9.22 shows examples of F-V curves that would be obtained in patients with increased airway resistance, such as in a patient with chronic obstructive pulmonary disease (COPD). Note the scooped-out appearance of the expiratory curve.

The F-V loops are helpful for evaluating a patient's response to bronchodilator therapy. Fig. 9.23 shows two flow-volume loops that reflect a patient's response to an aerosol treatment with a β-adrenergic agent (e.g., albuterol). Note the improvement in expiratory flow. In the inner loop, a high expiratory flow can be seen at the start of expiration; this spike in flow is an artifact that reflects the release of gas trapped in the patient circuit during inspiration. The clinician can confirm this finding clinically by noting whether the corrugated tubing of the patient circuit "exhales" at the start of expiration.

ASSESSING PATIENT-VENTILATOR ASYNCHRONY

Patient-ventilator asynchrony has been identified as one of the major issues in the management of patients on ventilation. As discussed in Chapter 18, asynchrony can be simply defined as a

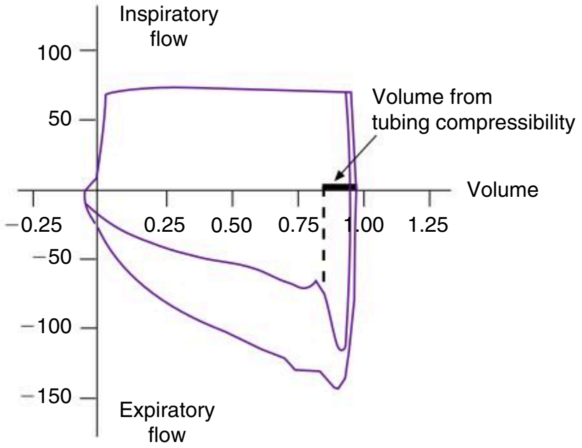

Fig. 9.23 Two F-V loops produced during volume ventilation *(constant flow waveform)*. The inner loop indicates increased airway resistance. The outer loop represents the patient's response to bronchodilator therapy. Note the improvement in expiratory flow. (NOTE: The high expiratory flow spike in the lower right corner of the inner loop results from gas decompression of the patient circuit. The initial expiratory flow spike is an artifact and represents release of the volume of gas trapped in the patient circuit at the beginning of the breath.) (Redrawn from Nilsestuen JO, Hargett K: Managing the patient-ventilator system using graphic analysis: an overview and introduction to Graphics Corner, *Respir Care* 41:1105—1122, 1996.)

mismatching between the patient's ventilatory drive and the response of the ventilator (Key Point 9.4). One type of asynchrony may occur at the onset of breath when the ventilator either delivers a premature breath or fails to recognize a patient effort. These situations are often referred to as trigger asynchrony (Fig. 9.24).

Trigger asynchrony can also be assessed using a P-V loop. Fig. 9.25A shows how the patient's inspiratory effort results in a considerable reduction in pressure below the PEEP level, creating the characteristic "fish tail" appearance. In Fig. 9.25B, trigger sensitivity has been adjusted, resulting in an improved trigger synchrony.

In Fig. 9.26 the arrows are pointing at a premature initiation of a breath independent of time or patient effort. This is often referred to as "autotriggering" and may be caused by too sensitive a trigger setting or a leak in the patient-ventilator circuit. A convenient method to differentiate an inappropriately set trigger sensitivity resulting in autotriggering from a leak is to observe the P-V and F-V tracings as shown in Fig. 9.27A and B.

Asynchrony can also occur when inspiratory flow from the ventilator does not match the patient's demands (i.e., flow asynchrony) or when the patient wants inspiration to end but the ventilator fails to cycle to exhalation (i.e., cycle asynchrony). Flow asynchrony can occur when the set flow rate, as in volume control ventilation, is insufficient to meet the patient's inspiratory demands. Notice the deflection *(arrows)* in the pressure scalar midway through inspiration, which creates an M-shaped pressure pattern associated with flow asynchrony (Fig. 9.28A). Remedies for flow asynchrony may include increasing the set flow in

Key Point 9.4 Asynchrony occurs when the neural ventilatory demands of the patient are not recognized by the ventilation.

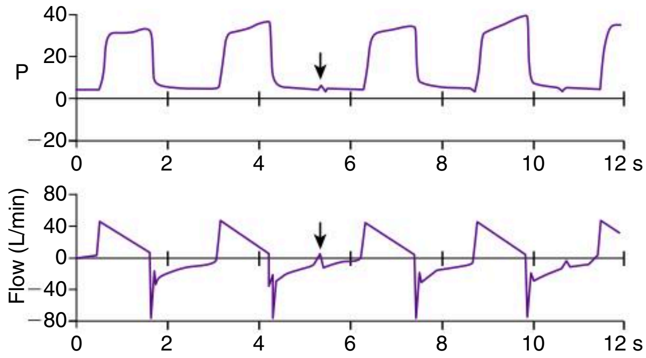

Fig. 9.24 Ventilator graphic demonstrating trigger asynchrony. Notice that the *arrows* point to a change in baseline pressure and flow without a response from the ventilator. This situation is often seen if the ventilator's sensitivity is set to low.

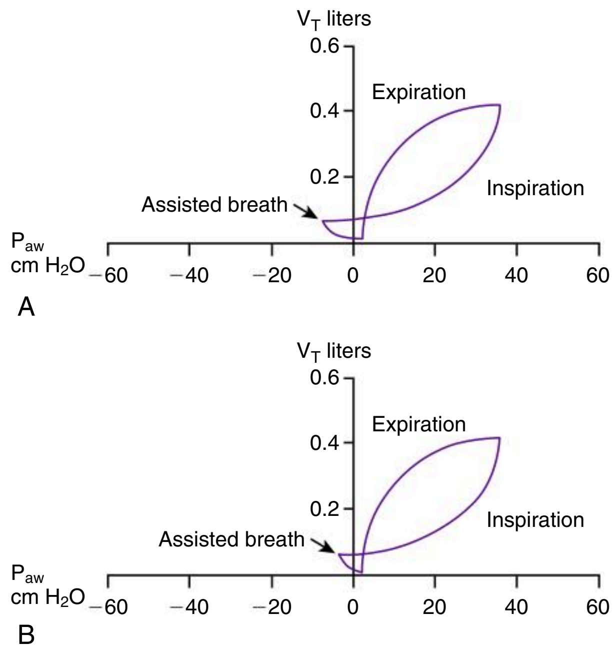

Fig. 9.25 Pressure-volume loops illustrating trigger asynchrony. (A) Deflection below the set level of PEEP, indicating increased patient effort to trigger a breath. (B) Trigger sensitivity has been adjusted, resulting in a minimal effort to initiate the breath.

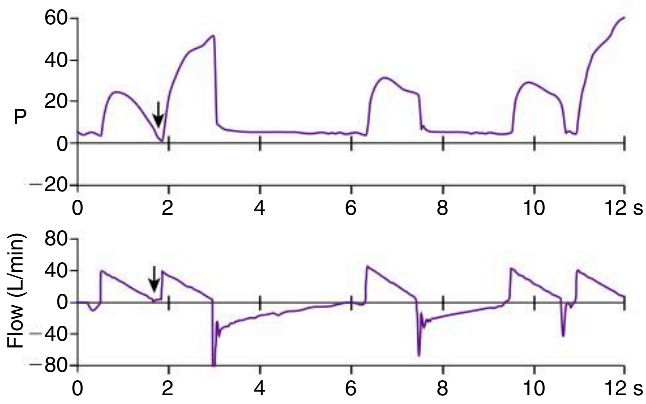

Fig. 9.26 Pressure and flow scalars showing the effects of "autotriggering."

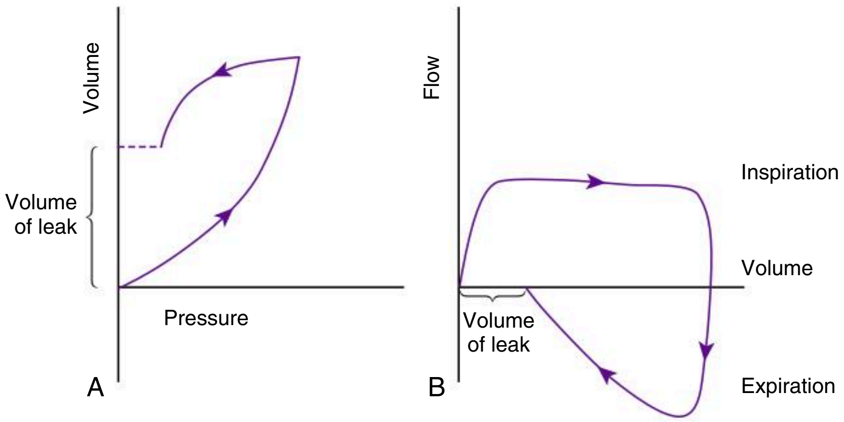

Fig. 9.27 Pressure-volume loop (A) and flow-volume loop (B) indicating an air leak.

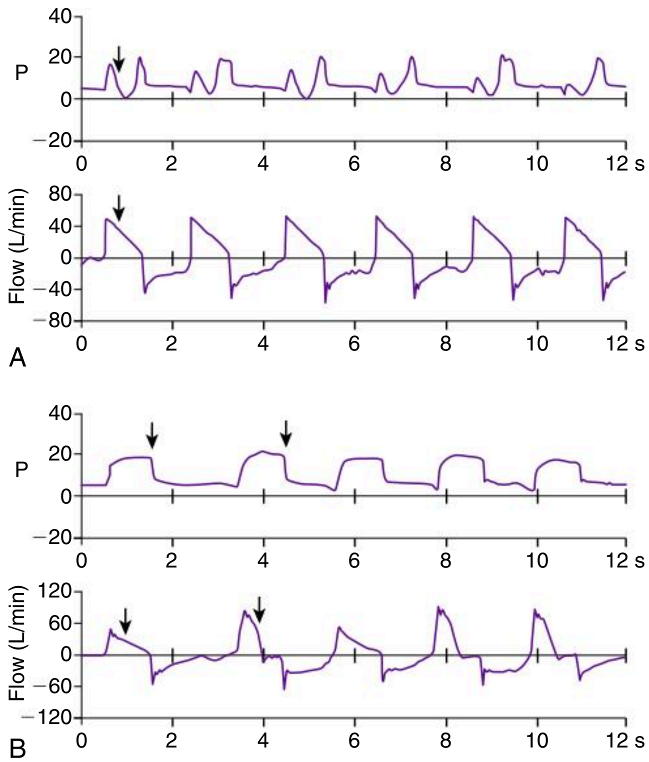

Fig. 9.28 (A) Pressure and flow scalars demonstrating flow asynchrony. (B) After the patient was switched to volume control plus (VC+), the contour of the pressure pattern became stable *(first breath)*. Notice how the delivered flow rate changed between the first and second breath in response to patient demand and flow asynchrony is avoided.

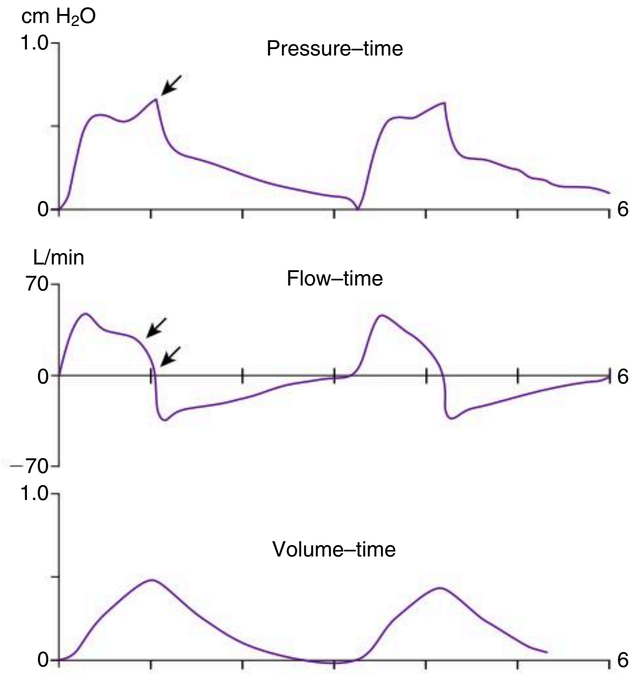

Fig. 9.29 Pressure, flow, and volume scalars illustrating a patient receiving 5 cm H_2O of pressure support. The patient's neural timing precedes the end of the mechanical inflation and results in a pressure spike *(large arrow)* on the pressure waveform. Note the rapid decline in the inspiratory flow waveform at the end of inspiration *(double arrows)* as a result of the patient's active exhalation. (From Nilsestuen JO, Hargett KD: Using ventilator graphics to identify patient-ventilator asynchrony, *Respir Care* 2005;50:202–234.)

volume-targeted ventilation, changing to a pressure-targeted breath, switching to hybrid breath type such as volume control plus (VC+), pressure-regulated volume control (PRVC), or autoflow. Fig. 9.28B illustrates the flow scalar changes that occur when the patient was switched to VC+. Notice how the delivered flow rate changes between the first and second breaths in response to patient demand and flow asynchrony is avoided (see Fig. 9.28B).

Failure to cycle or termination asynchrony often results in an inappropriate set T_I during a mandatory breath or an incorrect flow termination level on a spontaneous breath. Fig. 9.29 is an example of cycle asynchrony. The arrow points to rise in PIP at the end of inspiration created by the patient actively exhaling to end inspiration.

ADVANCED APPLICATIONS

Auto-PEEP and Air Trapping

Auto-PEEP, sometimes referred to as *intrinsic PEEP* or *air trapping*, occurs when the patient does not complete exhalation before

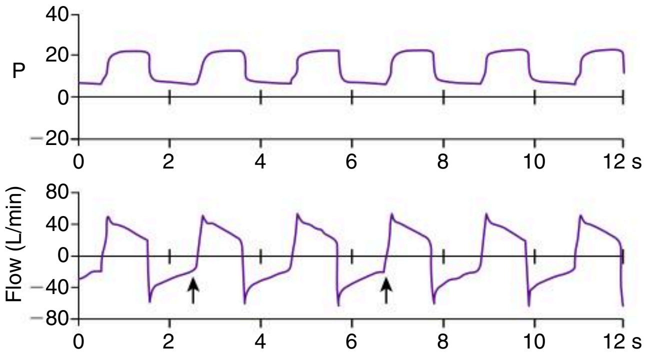

Fig. 9.30 Pressure and flow scalars demonstrating auto-PEEP. The *arrows* on the flow scalar show how flow does not return to baseline before the beginning of the next breath.

the onset of the next breath. Chapter 17 discussed the causes, occurrence, and remedy in detail. Fig. 9.30 indicates pressure and flow scalars for a patient demonstrating auto-PEEP.

Auto-PEEP initially can be observed on a P-V curve (Fig. 9.31A) and F-V loop (see Fig. 9.31B). The characteristic finding is the appearance of an incomplete exhalation with the expiratory portion of the loop not returning to baseline *(arrow)*. It is interesting to note that an air leak would look similar to auto-PEEP.

Titrating PEEP

Several methods can be used to correctly set PEEP, including observing changes in P-V loops as PEEP levels are changed. As previously discussed, the slope of the isoflow line reflects lung-thorax

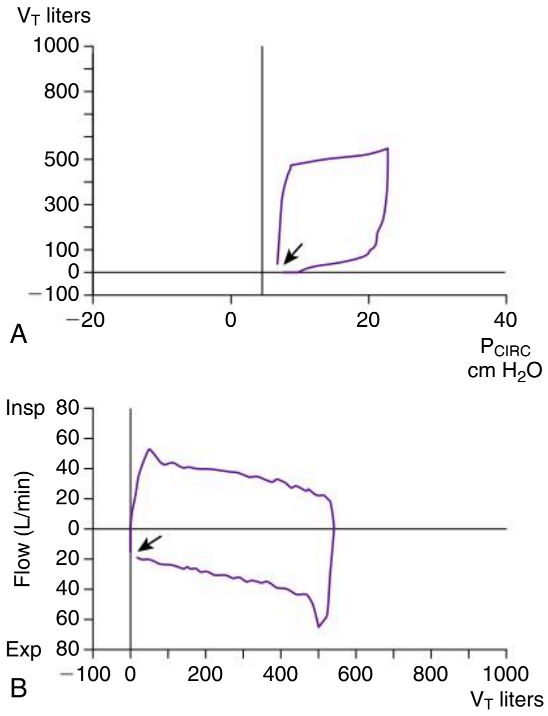

Fig. 9.31 (A) Pressure-volume loop demonstrating the presence of auto-PEEP. (B) Flow—volume loop demonstrating the presence of auto-PEEP. Notice that the expiratory portion of the P-V loop and the F-V loop does not return to baseline.

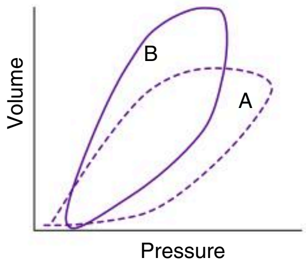

Fig. 9.32 Pressure-volume loops showing the effects of increasing levels of applied PEEP on lung-thorax compliance. (A) Effects of 0 cm H_2O of applied PEEP (decreased compliance). (B) Effects of 5 cm H_2O of applied PEEP (increased compliance).

compliance (see Fig. 9.19). As shown in Fig. 9.32, the slope of loop *A* is less than loop *B*, indicating that *B* represents a more compliant lung-thorax unit. Careful examination of these two curves shows that the curve *B* has a higher baseline (PEEP) level than curve *A*, demonstrating that the application of a higher PEEP level results in improved compliance.

APRV Settings

Airway pressure release ventilation (APRV) is often used as lung recruitment mode of ventilation. One of the unique features of this mode is the inversing of high-pressure time to that of low pressure. Graphics can be useful in determining the setting of high-pressure and low-pressure times to create a period of static flow (see Chapter 23). Additionally, this mode by design is often configured to generate auto-PEEP (Fig. 9.33).

Upper and lower inflection points can be used to determine the high and low PEEP settings in APRV. Fig. 9.34 provides an example of how the upper and lower inflections points affect the pressure scalar and P-V loop for during APRV.

Integrated Ventilator and Esophageal Graphics

Several ventilators provide an auxiliary pressure monitoring port that can be connected to an esophageal catheter. Esophageal pressure measurements may be employed to determine transpulmonary pressure (P_{TP}), which can then be used to set plateau and PEEP pressures. Additionally, esophageal manometry is often

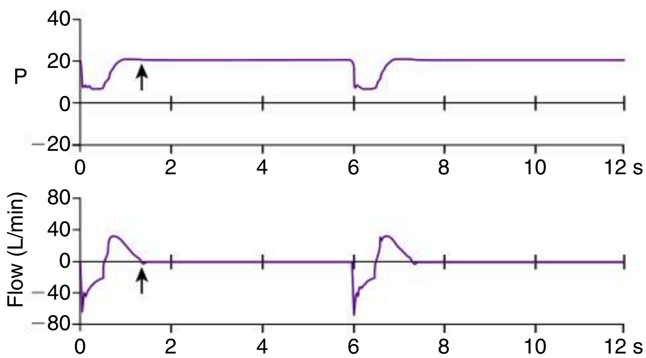

Fig. 9.33 Pressure and flow scalars for a patient receiving airway pressure release ventilation (APRV). Note the extended high-pressure time, short low-pressure period, and resulting auto-PEEP. The *arrows* are pointed to the period of constant pressure with zero flow. This period is thought to promote recruitment of low compliant alveolar units.

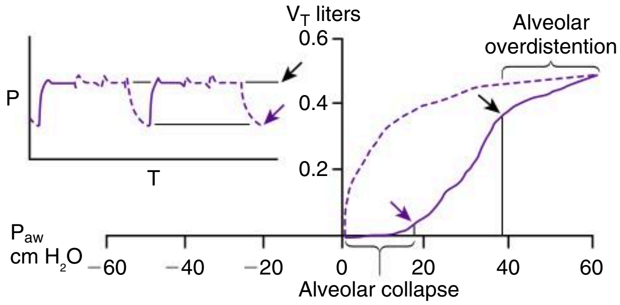

Fig. 9.34 Ventilator graphics illustrating how the upper and lower inflection points for an airway pressure release ventilation (APRV) breath would appear for a pressure scalar and a P-V loop. (Settings for APRV are often established by institutional protocol or through waveform analysis. See Chapter 23 for a detailed discussion on APRV).

used in conjunction with scalars to further identify patient-ventilator asynchrony, as shown in Fig. 9.35.

Assessing Overdistention During Pressure-Controlled Ventilation

Determining the appropriate amount of pressure to use with PC-CMV or PC-IMV can often be a challenging procedure. Although V_T delivery should be a primary criterion when setting the rise in pressure above baseline (PC + PEEP), often a secondary criterion can be used to avoid overdistention of the lung. Fig. 9.36 illustrates how ventilator graphics can be used to set ventilation parameters. Just as graphics can be used to set baseline pressures, they also can aid in determining the appropriate pressure level when a pressure-controlled breath is delivered. Notice in Fig. 9.36 how at the end of inspiration the P-V loop flattens out, creating a pressure overshoot sometimes referred to as a "bird beak." Compare the V_T delivery at 15 cm H_2O of pressure with that of 18, and notice that there is little difference between the two pressure levels. When administering ventilation to a premature infant, keeping the peak pressures at a minimum is critical. In this case the PC level could be dropped to 15 with little effect on V_T delivery.

Fig. 9.37 was obtained from an adult patient receiving PC-CMV. Again, notice the pressure overshoot creating a "bird beak" appearance on the P-V loop. Point *B* represents the peak inspiratory pressure, and point *A* indicates the pressure at which V_T delivery is optimized in terms of pressure. Note the difference in lung compliance between the two pressure levels indicating that pulmonary mechanics would be optimized at 20 cm H_2O of ventilating pressure.

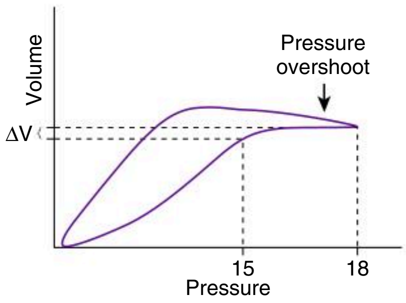

Fig. 9.36 Pressure-volume loop showing the effects of overdistention of the lung during pressure-controlled intermittent mandatory ventilation (PC-IMV).

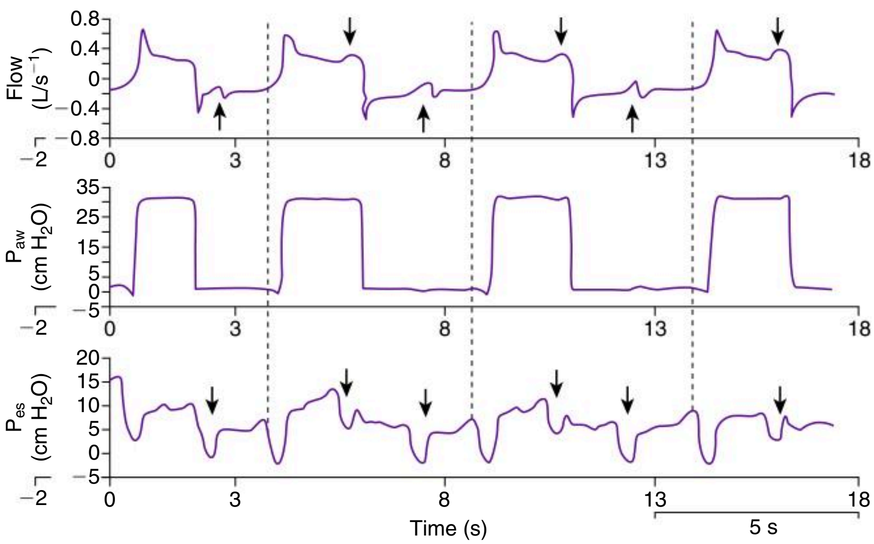

Fig. 9.35 Flow, air pressure (P_{aw}), and esophageal pressure (P_{es}) in a patient with chronic obstructive pulmonary disease (COPD) during PSV. *Dotted lines* indicate the beginning of an inspiratory effort that triggers ventilator gas flow. *Black arrows* in the P_{es} curve indicate patient efforts that did not trigger ventilatory flow. Note the time delay between the beginning of the effort and ventilator triggering. Ineffective efforts occur during both mechanical inspiration and expiration. During inspiration, the *flow scalar* can be used to identify ineffective patient efforts and a rise in the inspiratory flow. During expiration, ineffective efforts are identified by *open arrows* showing a small convex shape in the flow curve. Note how no apparent change occurs in P_{aw}. (From Kondili E, Prinianakis G, Georgopoulos D: New concepts in respiratory function, *Br J Anaesthesiol* 91:106—119, 2003.)