Key Point 12.3 Permissive hypercapnia is generally avoided for those patients who demonstrate intracranial lesions.

decreased myocardial contractility, arrhythmias, vasodilation, and increased sympathetic activity. A common finding in patients receiving PHY is increased cardiac output, a normal systemic blood pressure (BP), and pulmonary hypertension.[23] If the patient's sympathetic response is impaired or blocked, or if cardiac function is impaired, an increase in cardiac output might *not* occur, allowing the vasodilatation to result in hypotension.[19]

The exact response of the cardiovascular system to PHY is difficult to predict; therefore PHY should be used with caution. This is particularly true when working with patients with any of the following cardiovascular conditions: cardiac ischemia, left ventricular compromise, pulmonary hypertension, and right heart failure (Key Point 12.4).[22]

Finally, it is worth noting that elevated CO_2 or decreased pH may affect regional blood flow; skeletal and smooth muscle function; nervous system activity; and endocrine, digestive, hepatic, and renal system functions. Although these effects have not caused significant concern in the clinical setting, further research in these areas is warranted to improve our understanding of this ventilatory strategy.

Clinical Scenario: Permissive Hypercapnia

A 30-year-old man with ARDS has been on ventilatory support for 5 days. Current settings are $V_T = 500$ mL; $f = 12$ breaths/min; peak inspiratory pressure (PIP) = 37 cm H_2O; and $P_{plat} = 29$ cm H_2O. The patient is 5-ft, 8-in tall and has an IBW of 70 kg. ABGs show pH = 7.24 and P_aCO_2 = 64 mm Hg. What change is appropriate to return his P_aCO_2 to normal? If we tried to increase his V_T, pressures would increase. If we increase *f*, the desired f would be

$$\text{Desired f} = 12 \times 64/40 = 19 \text{ breaths/min}$$

This equation assumes that we want to maintain a normal P_aCO_2 of 40 mm Hg. One might suspect that the increased rate would also lead to air trapping, an increase in mean airway pressure, and an increased risk for lung injury. However, in patients with ARDS, lung units are more likely to empty quickly (short time constants). We might increase the rate slightly and allow P_aCO_2 to remain high (i.e., PHY). To protect the patient from increasing airway pressures, it might be appropriate to use pressure ventilation.

The use of PHY is restricted to situations in which the target airway pressure is at its maximum and the highest possible rates are being used. Although no adverse short-term effects of PHY have been noted for most patients, it is not known whether any long-term effects occur. The risks for hypercapnia are considered by some to be preferable to the high P_{plat} required to achieve normal CO_2 levels. This represents a significant shift in thinking in regard to ventilator management and ARDS.[24]

Key Point 12.4 Permissive hypercapnia should be used with caution when treating patients demonstrating cardiac ischemia, left ventricular compromise, pulmonary hypertension, and right heart failure.

Airway Clearance During Mechanical Ventilation

During mechanical ventilation, several techniques can be used to help clear secretions from the airway. These procedures differ somewhat from those used with nonintubated, spontaneously breathing patients. Included in this section are discussions of the following topics: suctioning, aerosol delivery, postural drainage and percussion, and fiberoptic bronchoscopy. High-frequency percussive ventilation can also assist with secretion clearance.

SECRETION CLEARANCE FROM AN ARTIFICIAL AIRWAY

Clearing secretions from the ET or tracheostomy tube (TT) of mechanically ventilated patients is an important component of bronchial hygiene therapy. Although it is not uncommon to see a physician's order read "Suction Q 2 hr," suctioning at fixed intervals is not appropriate and should be performed *only* when necessary (i.e., based on patient assessment findings).

Suctioning a patient's artificial airways involves insertion of a suction catheter into the patient's trachea and application of negative pressure as the catheter is gradually withdrawn.[25] Suctioning a patient with an artificial airway typically involves *shallow* suctioning, in which the catheter is inserted to a depth that approximates the length of the artificial airways. *Deep* suctioning involves inserting the catheter into the artificial airway until a resistance is met. Once the resistance is encountered, the catheter is withdrawn approximately 1 cm before applying negative pressure.

Two methods of suctioning are typically described on the basis of the type of catheter used: the open suctioning technique and the closed suctioning technique. The *open-circuit technique* requires disconnecting the patient from the ventilator; the *closed-circuit technique* can be performed without removing the patient from the ventilator. With the closed-circuit technique, a sterile, inline suction catheter is incorporated into the ventilator circuit, thus allowing passage of the catheter into the ET and trachea without disconnecting the patient from the ventilator (Key Point 12.5).

Suction catheters are generally made of transparent flexible plastic that is rigid enough to allow it to be easily inserted into the artificial airway but flexible enough to negotiate turns and not cause trauma to the airway. Catheters are smooth tipped with two or more side holes near the distal end (Fig. 12.3). (It is thought that these smooth-tipped catheters with side holes may help reduce trauma to the mucosa.[26])

Key Point 12.5 Two methods of endotracheal suctioning can be performed on the basis of the type of catheter used: *open-circuit technique* and *closed-circuit technique.*

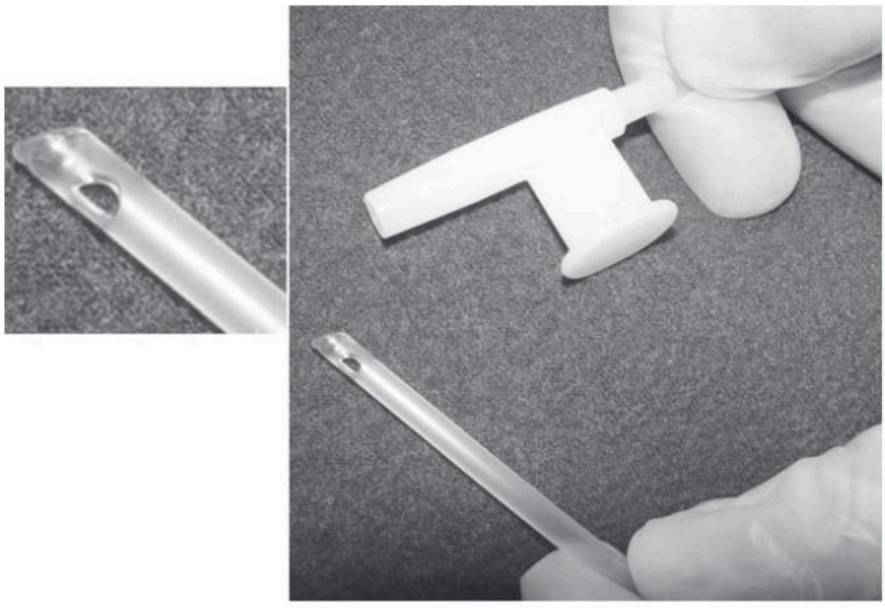


Fig. 12.3 Flexible suction catheter for lower airway suctioning showing rounded tip with side port *(cutaway of photo)*.

The proximal end of the catheter connects to a collecting canister via a large-bore plastic tube. A thumb port located at the proximal end of the suction catheter allows the operator to control the suction pressure. When it is covered, suction pressure is applied to the catheter and into the airway. The suction pressure applied should be the lowest possible pressure required to effectively clear secretions.[25] Table 12.1 provides a list of suggested suction pressure levels. These recommended suction levels are based on current practice, although it is common to see higher than recommended suction pressures used in many clinical settings. It is important to note that to date no experimental studies are available to support these values.

The catheter length should be long enough to reach a mainstem bronchus. This requires a catheter length of about 22 inches (56 cm).[26] Note that in infants and in patients with recent tracheal reconstructive surgery or pneumonectomy, the suction catheter should not be inserted more than 1 cm below the distal tip of the ET.[27]

Remember that the left mainstem bronchus is narrower and branches at a more acute angle than the right bronchus. Consequently, suction catheters often enter the right rather than the left bronchus. A special-tipped suction catheter is available with a bend at the distal end to help facilitate left bronchial suctioning, particularly if the patient is supine or lying on the left side or if the head is turned to the left. Left bronchus suctioning is easier when the patient has a TT in place rather than an ET.[27]

TABLE 12.1 Patient Size and Appropriate Suction Levels

Patient	Range	Maximum
Adults	−100 to −120 mm Hg	−150 mm Hg
Child	−80 to −100 mm Hg	−125 mm Hg
Infant	−60 to −100 mm Hg	−100 mm Hg

The diameter of the suction catheter selected is governed by the internal diameter of the artificial airway. It is generally accepted that the diameter of the suction catheter should not exceed 50% of the internal diameter of the artificial airway for children and adults and 30% of the internal diameters for infants.[25] Suction catheter sizes are based on French units. French units refer to the circumference of the tube. (NOTE: Circumference equals diameter multiplied by 3.1416 [π].) Because ETs are sized in centimeters and suction catheters are sized in French units, a conversion is required to estimate the correct size (Box 12.2).

Suctioning should be preceded by hyperoxygenation with 100% O_2 for 30 seconds, followed by hyperoxygenation with 100% O_2 for 1 minute after suctioning is complete, especially in patients who are hypoxemic before or during suctioning.[28] This can be done manually with a resuscitation bag, although this approach does not guarantee V_T or pressure, and it has been shown to be ineffective in delivering an F_IO_2 of 1.0.[25] Hyperoxygenation is therefore best accomplished using a temporary O_2-enrichment program that is available on many microprocessor ventilators.

The duration of suctioning should be brief and must not exceed 15 seconds.[25] Shallow suctioning is recommended over deep suctioning, particularly because deep suctioning has not been shown to be superior and may be associated with significantly greater chance of trauma to the tracheal mucosa. Although there is some

BOX 12.2 Estimating Correct Suction Catheter Size Based on Endotracheal Tube (ET) Size

Multiply ET size by 3. This converts the ET size to French units (Fr). Then divide this number by 2 to use half or less of the ET diameter.
For example: With a size 8 ET, 3 × 8 = 24; 24/2 = 12.
A size 12-Fr suction catheter would be appropriate.

debate regarding intermittent versus continuous suctioning, many clinicians choose applied suction intermittently rather than continually as it is withdrawn.[29,30]

Hazards and Complications of Suctioning

Loss of suction pressure may be caused by a leak in the system or because the collection canister is full. All connections should be checked, including ensuring that the suction jar is properly seated and screwed on tightly. In cases in which the collection canister is full, a float valve at the top of the canister will close the suction line to prevent the transmission of suction to the wall connection line.

Suctioning can cause a great deal of discomfort and anxiety. Stimulation of the airway with the catheter commonly induces coughing and can result in bronchospasm in patients with reactive airways. Suctioning can also cause hemorrhage, airway edema, and ulceration of the mucosal wall if it is performed improperly.[30]

The severity of the complications associated with suctioning is generally related to the duration of the procedure, the amount of suction applied, the size of the catheter, and whether oxygenation and hyperventilation are done appropriately. Reductions in lung volume can occur with suctioning and lead to atelectasis and hypoxemia. Note that to avoid atelectasis, the clinician should limit the duration of suctioning and the amount of negative pressure applied to the patient's airways. Hyperoxygenation and hyperventilation of the patient before and after suctioning can also reduce many of the complications associated with suctioning. It is also important to recognize that there is a temporary loss of applied PEEP when a patient is disconnected from the ventilator, which in turn can increase the severity of hypoxemia.

Cardiac arrhythmias can also occur during aggressive suctioning. Tachycardia is generally attributed to hypoxemia and irritation caused by the procedure; bradycardia can occur if the catheter stimulates vagal receptors in the upper airways.[31] Hypotension may occur as a result of cardiac arrhythmias or severe coughing episodes. Hypertension may occur because of hypoxemia or increased sympathetic tone resulting from stress, pain, anxiety, or a change in hemodynamics from hyperinflation (Case Study 12.2).[32,33]

Secretion removal is critical in patients with small airways, particularly infants and children, because of the smaller luminal ETs. Suction catheters can even result in pneumothorax in infants if the suction catheter perforates a bronchus.[28] Cross-contamination of the airway can occur if suctioning is not performed using sterile conditions.[34]

As previously mentioned, patients with closed head injuries usually have increased ICP. The simple process of inserting the suction catheter without suction being applied in patients with severe brain injury can raise the increased mean intracranial pressure, mean arterial pressure, and cerebral perfusion pressure.[32,35] This is particularly worrisome in this group of patients. If ICP is being monitored, pressures should be observed before and during suctioning. Oxygenating and hyperventilating the patient are important in this situation. It may even be appropriate to pretreat the patient with topical anesthetic approximately 15 minutes before the procedure to help reduce the risk for increasing ICP.[36,37]

Case Study 12.2

Assessment During Suctioning

During suctioning of a ventilated patient, the therapist notices a cardiac monitor alarm. The patient's heart rate has increased from 102 to 150 beats/min. What should the therapist do?

See Appendix A for the answer.

Closed-Suction Catheters (Inline Suction Catheters)

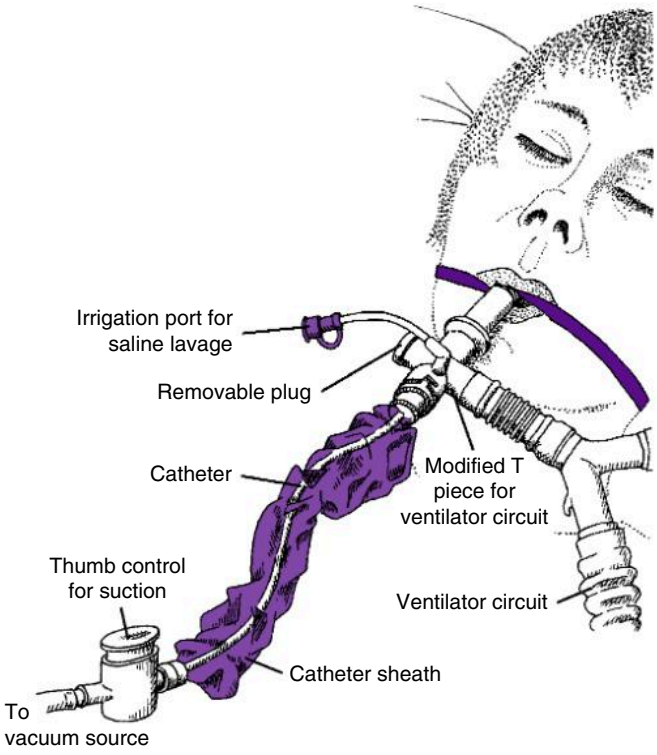
The closed-suction procedure is considered equally effective as the standard open-suction procedure.[38,39] The closed-suction procedure uses inline catheters that are encased in clear plastic sheaths. The plastic sheaths are attached to special assemblies that connect to a patient's ventilator circuit, near the Y-connector (Fig. 12.4).[40] Notice that inline catheters may add weight and increase the tension on the ET.

The advantage of using the closed-suction technique is that disconnecting the patient from the ventilator can be avoided. This is especially important in patients receiving high F_IO_2 values and PEEP because disconnecting the patient from the ventilator can increase the likelihood of hypoxia and alveolar collapse because of alveolar derecruitment. Another advantage of this technique is that it reduces the risk for contaminating the airway and lungs when patients are disconnected from the ventilator. For example, using a manual resuscitation bag may introduce contamination into the patient's lower airways when a single-use disposable suction catheter, which is accidentally contaminated by the handler, is used to suction a patient. In addition, aerosolized particles from the ventilator circuit can be released into the air during disconnection of the ventilator circuit, thus presenting a potential risk for contamination to the caregiver. Using inline suction avoids these problems and has been shown to reduce the incidence of ventilator-associated pneumonia (VAP).[41] Specific indications for closed-suction catheters are listed in Box 12.3.[42]

Although manufacturers typically recommend that inline catheters be changed daily, studies have shown that there is no increase in mortality, VAP, or length of stay in the hospital when the inline catheters are left in longer.[42-45] Weekly changes do not seem to increase the incidence of VAP compared with daily changes. In addition, changing less frequently reduces the cost of patient care.[46] (NOTE: Inline suction catheters should be changed more often than weekly if the device mechanically fails or becomes excessively soiled.)

As with regular suctioning, the procedure of hyperoxygenation of the patient is needed when closed suctioning is performed.[47] Hyperoxygenation is best accomplished using the ventilator as opposed to a manual resuscitation bag. However, different types of problems can occur with inline catheters compared with use of open-suctioning methods. Sometimes the catheter remains in the airway after suctioning or migrates into the airway between procedures. The clinician should ensure the suction catheter is withdrawn from the airway after suctioning. During pressure ventilation, this increases R_{aw} and can affect the patient's V_T delivery. In addition, when the catheter is rinsed with saline after the procedure, there is a risk for accidentally allowing some of the saline to go into the patient's airway.[26] Reduced pressure in the circuit during the suctioning procedure caused by using a high suction pressure can cause the ventilator to trigger. Aside from these few problems, the closed-suction catheter is effective and advantageous.

A



B

Fig. 12.4 (A) A closed-system suction catheter. (B) Labeled parts of the self-contained closed-system suction catheter. (Based on the Kimberly Clark Ballard Trach Care Closed Suction System.) (A From Cairo JM, Pilbeam SP: *Mosby's respiratory care equipment,* ed 11, St. Louis, MO, 2022 (Cardinal Health Respiratory Care Products and Services, Dublin, Ohio), Mosby. B From Sills JR: *The comprehensive respiratory therapist examination review: entry and advanced levels,* ed 5, St. Louis, MO, 2010, Mosby.)

BOX 12.3 Indications for Using Closed-Suction Catheter Systems

Unstable patients who are ventilated (e.g., in acute lung injury or acute respiratory distress syndrome) and have high ventilator requirements:

- High PEEP $\geq$10 cm H_2O
  - High P_{aw} $\geq$20 cm H_2O
  - Long inspiratory time $\geq$1.5 second
  - High F_IO_2 $\geq$0.6
- Patients who become hemodynamically unstable during suctioning with an open system and ventilator disconnection
- Patients who desaturate significantly (a drop in S_pO_2) during suctioning with an open system and ventilator disconnection
- Patients with contagious infections, such as active tuberculosis, in which open suctioning and ventilator disconnect may contaminate health care workers
- Patients on ventilation who require frequent suctioning, for example, more than 6 times a day
- Patients receiving inhaled gas mixtures (such as nitric oxide or heliox therapy) that cannot be interrupted by ventilator disconnection

Aspiration of Subglottic Secretions

Cuffed ETs have been used for years to protect the patient's airway from aspiration. However, even while aspiration of large volumes of material (gastric regurgitation) is generally avoided with a cuff, silent aspiration does occur.

High-volume low-pressure cuffs represent the majority of ETs used in the acute care setting today. Although the lower cuff pressures used with these ETs reduces the potential for tissue damage, these devices may not prevent silent aspiration of subglottic secretions if the cuff pressure is too low. Silent aspiration of subglottic secretions can increase bacterial colonization of the tracheobronchial tree and result in VAP, which is also referred to as *endotracheal tube–associated pneumonia.*[26] (See Chapter 14 for a discussion of VAP.) Silent aspiration and VAP can occur with cuffed ETs for several reasons:

- Injury to the mucosa during insertion and manipulation of the tube after insertion
- Interference with the normal cough reflex
- Aspiration of contaminated secretions that pool above the ET cuff
- Development of a contaminated biofilm around the ET[48]

Silent aspiration occurs in the following manner. Large cuffs can develop longitudinal folds when inflated in the trachea. Liquid pharyngeal secretions leak through these folds (silent aspiration) into the lower airway. Increasing the cuff pressure does not completely eliminate this problem, which in turn can lead to VAP.[26] (It is worth

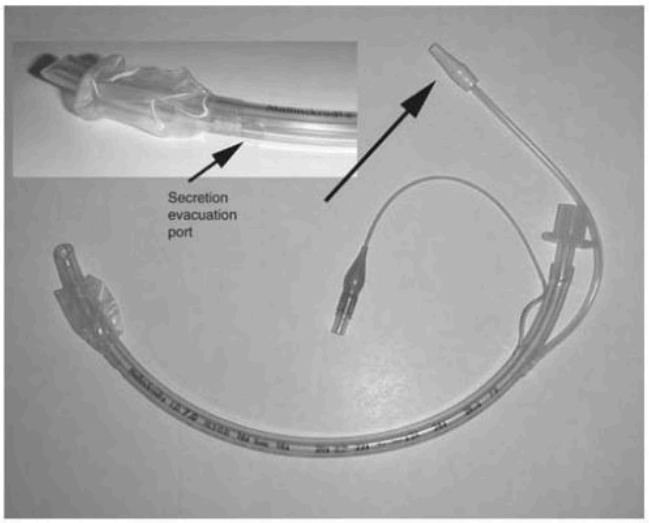


Fig. 12.5 Hi-Lo Evac endotracheal tube with endotracheal tube connector *(top)*, suction port connector, pilot balloon. Note the close-up of the suction lumen above the cuff. (From Cairo JM: *Mosby's respiratory care equipment*, ed 10, St. Louis, MO, 2018, Elsevier.)

mentioning that the incidence of VAP is between 10% and 60%, and it is associated with increased mortality.[49])

Specialized ETs that may reduce the incidence of silent aspiration have been developed (e.g., Hi-Lo Evac ET, Mallinckrodt, Covidien, Boulder, CO; Fig. 12.5). The Hi-Lo Evac ET has a suction port just above the cuff on the dorsal side of the tube to remove secretions above the cuff of the ET and reduce the risk for VAP associated with silent aspiration. The Hi-Lo Evac ET allows for the continuous aspiration of subglottic secretions (CASS). The manufacturer recommends using 20 mm Hg of continuous suction. Other advances in ET tube design that have been shown to reduce the incidence of silent aspiration include specially designed ET cuffs made of polyurethane or silicone. These specially designed ET tubes reduce the formation of longitudinal channels in the cuff, which provide openings for secretions to leak around the cuff and enter the lower airways.

Continuous suction tubes are more expensive than standard ETs and as a consequence are not typically inserted in all patients. However, some hospitals have policies to allow insertion of these tubes in emergency departments and during emergency intubations. For patients who may require an extended period on a ventilator with an ET in place, it may be appropriate to change the standard ET tube for the specialized tube.[26] CASS may be most effective in patients requiring intubation for more than 3 days.[50] Although the tube costs more than a standard ET, cost savings can be gained if the patient's length of stay in the intensive care unit (ICU) is reduced. Furthermore, the Centers for Disease Control and Prevention recommends the use of this device because it has been shown to reduce the incidence of nosocomial pneumonias or VAP.[34,50-53] One study showed a fivefold greater likelihood of VAP when CASS was not used.[52]

In general, complications associated with CASS are minimal. Use of CASS can result in severe damage to the airway if the inline catheter is placed in a fixed position. In a case reported in the literature, a fatal tracheal–innominate artery fistula occurred as a result of CASS. In this incident, the inline catheter was fixed to a tooth (the left upper molar) and its position was not changed, resulting in erosion of the tissues.[54]

In addition to silent aspiration, another source of bacterial colonization of the lungs is the presence of a biofilm that forms inside ETs and may serve as a source of bacteria. It is thought that these bacterial colonies can be dislodged from the inner lumen during standard suctioning procedures.[26]

In addition to CASS, another way of avoiding VAP may include decreasing colonization of bacteria in the stomach by maintaining an acid environment in the stomach and using nonabsorbable antibiotics to reduce the number of growing organisms.[49]

Normal Saline Instillation

An airway clearance technique used by many ICU clinicians involves the instillation 3 to 5 mL of sterile normal saline or half-normal saline into the airway (saline lavage), followed by hyperoxygenation (with 100% O_2) of the patient before suctioning. The intent of saline lavage is to loosen secretions and stimulate the patient to cough.[25,55]

Presently there is insufficient evidence to support the practice of instilling normal saline into the ET before suctioning. In fact, a number of recent studies indicate that this practice actually may be harmful.[25] Indeed, saline does not thin secretions, and instilling saline may increase the risk for dislodging bacteria-laden biofilm from the ET, which in turn can lead to the development of nosocomial pneumonia.[37,55] Saline instillation may also cause irritation to the airways, resulting in severe coughing episodes and bronchospasm in some patients.

It is also worth noting that less fluid is suctioned compared with the amount instilled into the airway during saline instillation. In addition, saline instillation can increase the volume of secretions in the airways and potentially add to airway obstruction.[56] It can also reduce oxygenation and increase a patient's sensation of dyspnea, particularly in older patients (i.e., older than 60 years).[57]

Assessment After Suctioning

The amount, color, odor, and physical characteristics of the sputum should be documented on a ventilator flow sheet along with evaluation of the breath sounds after suctioning. It is also important to check for bilateral breath sounds to assess the effects of suctioning and ensure that the ET has not changed position. It is worth mentioning that right mainstem intubation can occur during these types of procedures and might not always be detected with auscultation.[58] For this reason, some institutions have a standing order for a chest radiograph to be taken every 24 hours to ensure proper tube placement and check for any pathological changes from the previous film (Box 12.4).[59]

BOX 12.4 Routine Chest Radiographs

A study conducted by Krivopal and associates found that monitoring daily chest radiographs (CXRs) was not associated with reduced length of stay in the intensive care unit or the hospital or with a reduction in mortality compared with CXRs taken only when a change in the patient's condition warranted a chest film.[60] New findings on nonroutine CXRs resulted in a significantly greater number of patient interventions. Routine CXRs may not be as important in patient management compared with protocols that recommend the use of a CXR when the patient's condition warrants this evaluation.

BOX 12.5 Excerpts From the American Association for Respiratory Care (AARC) Clinical Practice Guidelines for Endotracheal Suctioning of Mechanically Ventilated Adults and Children With Artificial Airways

Indications
The need to remove accumulated pulmonary secretions as evidenced by:
- Patient's inability to generate an effective spontaneous cough
- Changes in monitored flow-volume graphics
- Deterioration of O_2 saturation or arterial blood gas (ABG) values
- Increased peak inspiratory pressure (PIP) with volume ventilation
- A decrease in V_T with pressure ventilation
- Visible secretions in the airway
- Acute respiratory distress
- Suspected aspiration of gastric or upper airway secretions

Contraindications
Most contraindications are relative to the patient's risk for developing adverse reactions or worsening clinical condition as a result of the procedure. When suctioning is indicated, there is no absolute contraindication because abstaining from suctioning to avoid possible adverse reaction may, in fact, be lethal.

Hazards and Complications
- Decrease in dynamic lung compliance and functional residual capacity
- Pulmonary atelectasis: reduction of lung volume
- Hypoxia or hypoxemia
- Hypoxia or hypoxemia: ventilator disconnection and loss of PEEP
- Tracheal or bronchial mucosal trauma: suction pressures
- Cardiac or respiratory arrest: extreme response to suctioning and ventilator disconnect
- Bronchoconstriction or bronchospasm
- Increased microbial colonization of the patient's lower airways
- Pulmonary hemorrhage or bleeding: trauma to the airways from suctioning
- Elevated intracranial pressure
- Cardiac dysrhythmias
- Hypertension
- Hypotension
- Routine use of normal saline instillation before endotracheal tube (ET) suctioning may be associated with excessive coughing, decreased O_2 saturation, bronchospasm, and dislodgment of bacterial biofilm that colonizes the ET into the lower airways.

Assessment of Need
Qualified personnel should assess the need for endotracheal suctioning as a routine part of a patient-ventilator system assessment.

Assessment of Outcome
- Improvement in the appearance of ventilator graphics and breath sounds
- Decreased PIP with narrowing of PIP-P_{plat}; decreased airway resistance or increased dynamic compliance; increased V_T delivery during pressure-limited ventilation
- Improvement in ABG values or saturation as reflected by pulse oximetry (S_pO_2)
- Removal of pulmonary secretions

Monitoring
The following should be monitored before, during, and after the procedure:
- Breath sounds
- O_2 saturation (S_pO_2)
- F_IO_2
- Respiratory rate and pattern
- Pulse rate, blood pressure, electrocardiogram (if indicated and available)
- Sputum (color, volume, consistency, odor)
- Ventilator parameters
- ABGs
- Cough effort
- Intracranial pressure (if indicated and available)

From the AARC Clinical Practice Guideline: endotracheal suctioning of mechanically ventilated patients with artificial airways, *Respir Care* 55:758–764, 2010.

The American Association for Respiratory Care (AARC) has produced an updated Clinical Practice Guideline (CPG) that outlines the procedure for endotracheal suctioning of patients on mechanical ventilation.[25] This CPG provides valuable information regarding patient preparation, the suctioning event and follow-up care, indications, contraindications, hazards and complications, limitations, need and outcome assessments, required resources, types of monitoring that should be used during and after the procedure, and infection control precautions (Box 12.5).

ADMINISTERING AEROSOLS TO VENTILATED PATIENTS

The delivery of therapeutic aerosols during mechanical ventilation has received considerable attention during the past decade. A number of drugs and agents can be administered to mechanically ventilated patients, including bronchodilators, corticosteroids, antibiotics, mucolytics, and surfactants.[61] Bronchodilators are the most frequently used drug administered by aerosol to mechanically ventilated patients.

Fig. 12.6 illustrates a variety of factors that must be considered when delivering aerosols to mechanically ventilated patients.[61,62] These factors include the following:
- Type and placement of aerosol-generating device used
- Ventilator mode and settings
- Severity of the patient's condition
- Nature and type of medication and gas used to deliver it

These factors are reviewed in more detail later in this section.

Aerosol administration of bronchodilators to mechanically ventilated patient is indicated for the treatment of bronchoconstriction or increased R_{aw}. The decision to administer a bronchodilator should be based on the patient's history and physical assessment findings. Use of ventilator graphics can support these findings (see Fig. 9.24). Box 12.6 summarizes the AARC CPG for the selection of an aerosol device and administration of a bronchodilator to a ventilated patient.[63]

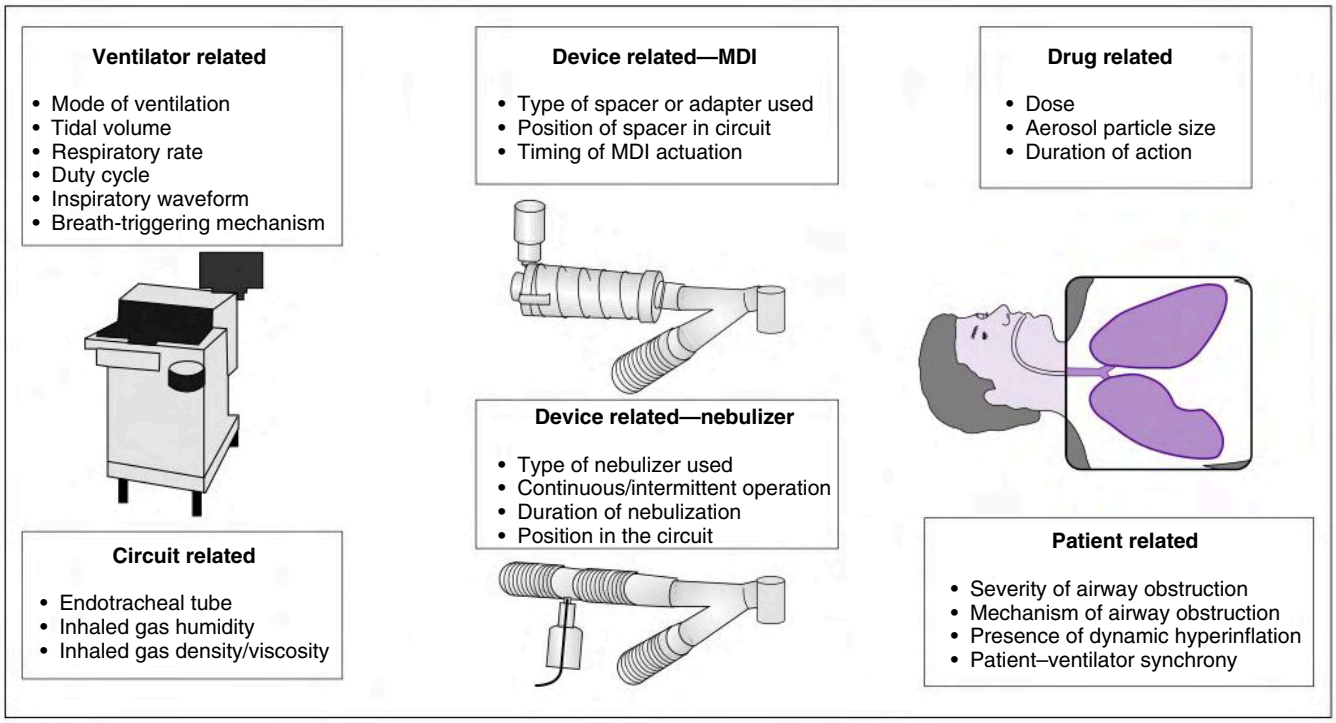


Fig. 12.6 Factors that influence aerosol delivery in mechanically ventilated patients: *MDI,* Metered-dose inhaler. (Reproduced with permission of the © ERS 2023: *European Respiratory Journal* 9(3):585—595; https://doi.org/10.1183/09031936.96.09030585. Published 1 March 1996.)

BOX 12.6 Excerpts From the American Association for Respiratory Care (AARC) Clinical Practice Guidelines for Selection of a Device for Administration of a Bronchodilator and Evaluation of the Response to Therapy in Mechanically Ventilated Patients

Indication

Aerosol administration of a bronchodilator and evaluation of response are indicated whenever bronchoconstriction or increased airway resistance is documented or suspected in mechanically ventilated patients.

Contraindications

Some assessment maneuvers may be contraindicated for patients in extremis, for example, a prolonged inspiratory pause for patients with high auto–positive end-expiratory pressure (PEEP). The use of certain medications also may be contraindicated in some patients. The package insert should be consulted for these product-specific contraindications.

Hazards and Complications

- Specific assessment procedures may have inherent hazards or complications, for example, a prolonged inspiratory or expiratory pause.
- Inappropriate selection or use of a device or technique variable may result in underdosing.
- Device malfunction may result in reduced drug delivery and may compromise the integrity of the ventilator circuit.
- Complications may arise from specific pharmacological agents. Higher doses of β-agonists delivered by pressurized metered-dose inhaler or nebulizer may cause adverse effects secondary to systemic absorption of the drug or propellant. The potential for hypokalemia and atrial and ventricular dysrhythmias may exist with high doses in critically ill patients.
- Aerosol medications, propellants, or cold, dry gases that bypass the natural upper respiratory tract may cause bronchospasm or irritation of the airway.
- The aerosol device or adapter used and the technique of operation may affect ventilator performance characteristics or alter the sensitivity of the alarm systems.
- Addition of gas to the ventilator circuit from a flowmeter or other gas source to power an inline small-volume nebulizer (SVN) may increase volumes, flows, and peak airway pressures, thereby altering the intended pattern of ventilation. The added gas source will also alter O_2 delivery. Ventilator setting adjustments and alarm changes made to accommodate the additional gas flow must be reset at the end of the treatment.
- Addition of gas from a flowmeter to an inline nebulizer in the ventilator circuit may result in the patient becoming unable to trigger the ventilator during nebulization, leading to hypoventilation.

Modified from AARC Clinical Practice Guideline: Selection of a device for administration of a bronchodilator and evaluation of the response to therapy in mechanically ventilated patients, *Respir Care* 44:105–113, 1999.

TYPES OF AEROSOL-GENERATING DEVICES

Two types of devices are used for administering aerosols to mechanically ventilated patients: pressurized metered-dose inhalers (pMDIs) and nebulizers, including small-volume (jet) nebulizers (SVNs), ultrasonic nebulizers (USNs), and vibrating mesh nebulizers (VMNs).[64] Historically, pMDIs and SVNs have been the most commonly used nebulizers but USNs and VMNs are becoming more widely used. The primary advantage of using USNs and VMNs is that these devices produce smaller aerosol particles than pMDIs and SVNs without the addition of gas into the ventilator circuit.[65,66]

Early in vitro and in vivo studies reported that drug deposition rates for aerosolized medications during mechanical ventilation ranged from only 1.5% to 3.0% for SVNs and pMDIs. More recent studies demonstrated that the deposition rates for SVNs can be significantly improved (up to 15%) when optimum conditions are used.[65] Deposition rates for pMDIs can range from as low as 2.0% to as high as 98%, depending on the delivery technique and whether a spacer is used.

Both pMDIs and SVNs can produce aerosol particles with a mean mass aerodynamic diameter of 1 to 5 μm. Although the physiological response of the patient is similar whether a pMDI or an SVN is used, pMDI doses may need to be adjusted to deliver an adequate amount of medication during mechanical ventilation (i.e., using four or more puffs). This may require doubling the dose that would typically be administered to a spontaneously breathing patient.[62]

Ventilator-Related Factors

As Fig. 12.6 illustrates, various ventilator-related factors can affect aerosol delivery. Tables 12.2 and 12.3 list various device-related factors that can affect medication delivery to mechanically

TABLE 12.2 Ventilator-Related Factors That Influence Aerosol Delivery in Mechanically Ventilated Patients

Ventilator-Related Factor	Effect on Aerosol Delivery[a]
Ventilator mode	Spontaneous breaths >500 mL improve aerosol delivery compared with mandatory breaths. VC-CMV is more effective for aerosol delivery compared with PC-CMV.
Tidal volume (V_T)	A set V_T that is large enough to include volume of the tubing and ET tube improves aerosol delivery and ensures that dead space is cleared of aerosol.
Respiratory rate	Lower respiratory rates improve aerosol delivery.
Duty cycle or T_I	Longer duty cycle (T_I/TCT) or longer T_I improves delivery.
Inspiratory waveform	Square waveform delivers less aerosol than decreasing ramp or sinusoidal waveforms.

[a]Metered-dose inhaler medication delivery not influenced by T_I, flow pattern, lung mechanics, or mode (volume-controlled versus pressure-controlled ventilation).

ET, Endotracheal tube; *PC-CMV,* pressure-controlled continuous mandatory ventilation; T_I, inspiratory time; *TCT,* total cycle time.

TABLE 12.3 Device-Related Factor to Optimize Bronchodilator Delivery During Mechanical Ventilation in Adults

Device-Related Factors	Effect on Aerosol Delivery
Position of aerosol device in circuit	The location of the aerosol device in the ventilator circuit significantly affects the amount of drug delivery and aerosol deposition.
Nebulizer-related factors	Nebulizer type: Vibrating mesh nebulizers, ultrasonic nebulizers, and pMDIs with spacer are more efficient than jet nebulizers. Intermittent and continuous nebulization: Intermittent nebulization synchronized with expiration is more efficient for aerosol delivery than continuous nebulizers. Residual dead volume: The greater the dead volume, the less amount of drug is nebulized. Jet nebulizers do not aerosolize below dead volume of 1–2.5 mL. Vibrating mesh nebulizers have smaller residual volumes than jet or ultrasonic nebulizers. Gas flow: The ultrasonic and vibrating nebulizers are not influenced by gas flow as they are electrically powered. Particle size is minimally affected with heliox. Heliox improves aerosol deposition by creating laminar flow that decreases impaction losses. Operating the jet nebulizer at a lower flow or pressure than the design will increase particle size and reduce delivery. Gas flow is inversely related to nebulization time with the jet nebulizer
pMDI-related factors	Synchronized pMDI actuations with inspiration increase aerosol delivery. Spacer: Using a chamber spacer with the pMDI reduces losses in the circuit and increases drug delivery up to sixfold. The efficiency of a bidirectional inline adapter was higher than the efficiency of a unidirectional inline adapter and achieved efficiency marginally less than chamber spacers. Use of chamber spacers with the pMDIs enhances aerosol administration to patients on mechanical ventilation. Bidirectional inline adapters are a better option than unidirectional low-volume inline adapters. Shaking the canister: The drug in the pMDI formulations are separated when standing. Therefore not shaking a pMDI canister reduces total and respirable dose up to 35%.

pMDI, Pressurized metered-dose inhalers.

Modified from Ari A, Fink JB: Factors affecting bronchodilator delivery in mechanically ventilated adults, *Nurs Crit Care* 15:192–203, 2010.

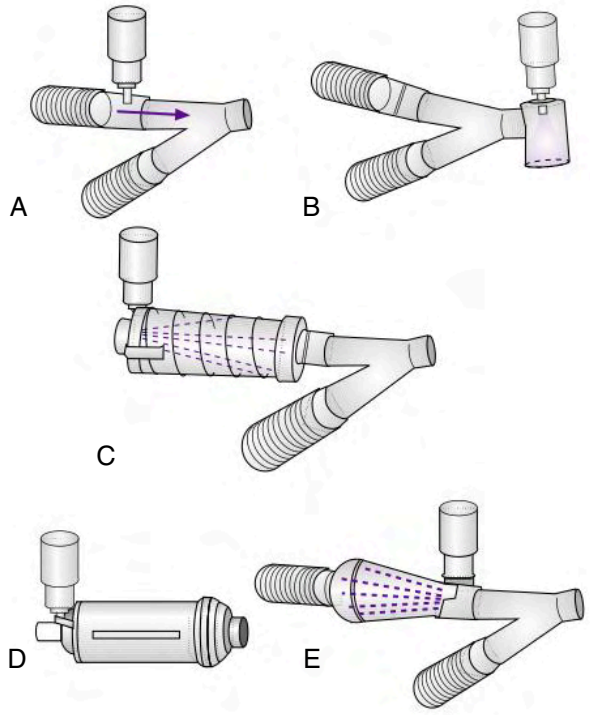


Fig. 12.7 Devices used to adapt a metered-dose inhaler to a ventilator circuit. (A) Inline device. (B) Elbow device. (C) Collapsible chamber device. (D) Chamber device. (E) Chamber device in which aerosol is directed retrograde into the ventilator circuit. (Reproduced with permission of the © ERS 2023: *European Respiratory Journal* 9(3):585—595; https://doi.org/10.1183/09031936.96.09030585. Published 1 March 1996.)

ventilated adults.[65-67] Although ventilator settings cannot always be adjusted for aerosol delivery, it can be helpful whenever possible to use low flow rates, higher V_Ts, and lower respiratory rates during the treatment.

The pMDI can be introduced into a ventilator circuit through an elbow adapter or with unidirectional and bidirectional inline chamber and spacer adapters. Elbow adapters are connected directly to the ET. Inline chambers and spacers are placed in the inspiratory limb of the ventilator circuit, as illustrated in Fig. 12.7. Several studies have demonstrated that inline chambers and bidirectional spacers produce considerably greater aerosol delivery than do elbow adapters and unidirectional spacers.[65] Elbow adapters, by virtue of their design, create a 90-degree connection with the circuit. Other abrupt angles in the ventilator circuit created by the Y-connector and inline suction catheters can provide points of impact and turbulence that interfere with aerosol delivery (Key Point 12.6). Recent studies suggest the best position for a pMDI is approximately 6 inches from the Y-connector.[65,66]

***Key Point* 12.6** Devices that create abrupt angles between the pMDI and the ET can significantly reduce aerosol delivery to the patient.

Patient-Related Factors

Patients with large amounts of secretions in the ET or who are experiencing severe bronchospasm present a special challenge for aerosol delivery. As airflow obstruction increases, the delivery of aerosol decreases. Thus the patient's condition can affect the aerosol delivery pattern. In patients with COPD and increased R_{aw}, intermittent delivery of nebulized bronchodilators (i.e., during inspiration) may be more effective than continuous delivery.[68] The presence of auto-PEEP (hyperinflation) and patient-ventilator **asynchrony** can also interfere with aerosol delivery.

Circuit-Related Factors

It is generally accepted that larger ETs (≥size 7) permit greater aerosol deposition.[69] This fact is particularly important to remember during pediatric ventilation because the internal diameter of the airway may be between 3 and 6 mm, which can reduce aerosol deposition because of the small size of the ET.[70]

Heated humidifiers can affect aerosol delivery. Increased humidity increases particle size and is likely to reduce the amount of medication delivered to the patient, regardless of the device.[71,72] However, bypassing the humidifier during a treatment is generally not advisable. In fact, placement of an SVN between the ventilator outlet and the humidifier may improve aerosol delivery from the device.[72,73] In addition, some nebulizer treatments take up to 30 minutes, and inhalation of dry gases for this amount of time may cause damage to the airway.[61,74]

Delivery of aerosolized bronchodilators is also affected by the delivery gas. Although previous studies stated that helium-oxygen mixtures could not be used to deliver aerosols because helium is a "poor vehicle" for aerosol transport, more recent studies have shown that helium-oxygen mixtures may improve aerosol deposition in patients with asthma by reducing airflow turbulence.[75]

Use of Pressurized Metered-Dose Inhaler During Mechanical Ventilation

The pMDIs present fewer technical problems than do the SVNs when used during mechanical ventilation. Furthermore, using a pMDI with a spacer has been shown to be more efficient than using a nebulizer in delivering a bronchodilator to the lower respiratory tract[76] (see the section on problems associated with SVNs).

The following procedure is recommended when administering aerosols to mechanically ventilated patients with a pMDI[65]:

1. Review the order, identify the patient, and assess the need for bronchodilator. (Suction airway if needed.)
2. Establish the initial medication dose (e.g., four puffs of albuterol).
3. Shake the pMDI and warm to hand temperature.
4. Place the pMDI in spacer adapter in the inspiratory limb of ventilator circuit.
5. Remove the heat-moisture exchanger (HME). (Do not disconnect humidifier if one is in use.)
6. Minimize the inspiratory flow during VC-CMV; increase T_I (>0.3 seconds) during PC-CMV.
7. Coordinate actuation of pMDI with the precise beginning of inspiration. (Be sure that mandatory breaths are synchronized with a patient's inspiratory effort. V_T must be large enough to compensate for the ventilator circuit, ET, and V_{Danat}.)
8. If the patient can take a spontaneous breath (>500 mL), coordinate actuation of the pMDI with a spontaneous breath initiation and encourage a 4- to 10-second breath hold. Otherwise, allow passive exhalation.

9. Wait at least 20 to 30 seconds between actuations. Administer total dose.
10. Monitor for any adverse responses to the administration of medication.
11. Assess the patient response to therapy and titrate dose to achieve desired effect.
12. Reconnect HME.
13. Document clinical outcomes and patient assessment.

Use of Small-Volume Nebulizers During Mechanical Ventilation

Although pMDIs and SVNs are most often used to deliver bronchodilators and corticosteroids, SVNs are commonly used to deliver mucolytics, antibiotics, prostaglandins, and surfactants.[62] Use of an external SVN powered by a separate gas source, such as an O_2 flowmeter, is a common method for delivery of aerosolized medications during mechanical ventilation (Key Point 12.7).[76,77] Fig. 12.6 and Box 12.7 illustrate various factors that can affect aerosol deposition with SVNs during mechanical ventilation.[66,67,78-80]

***Key Point* 12.7** When a patient requires a larger dose of a β-agonist, such as a patient with acute severe asthma, a nebulizer (e.g., SVN, USN, VMN) may deliver more medication into the respiratory tract than a pMDI with spacer.

BOX 12.7 Factors That Affect Aerosol Deposition With Small-Volume Nebulizers (SVN) During Mechanical Ventilation

The performance and rate of aerosol production of SVNs vary by manufacturer and even by production batch.

The volume of liquid (medication + diluent) placed in the SVN before the treatment and the dead volume (amount of medication trapped in the reservoir after the treatment that cannot be nebulized) affect aerosol dose delivery. (Using a 5-mL volume is recommended.)

Position of the SVN in the circuit is important. A better deposition occurs when the SVN is proximal to the humidifier.[72,73] High flows create smaller particles but speed the treatment, resulting in more aerosol being lost during the expiratory phase. Longer delivery time usually increases aerosol delivery. A flow of 6 to 8 L/min is typically recommended.

The duration of nebulization varies from 3 to 5 minutes for continuous nebulization and from 15 to 20 minutes or longer for intermittent nebulization. Continuous nebulization allows the main inspiratory line of the ventilator circuit to fill with aerosol particles during exhalation, although some studies suggest that nebulization only during inspiration may be more efficient because it eliminates aerosol waste during exhalation phase. (NOTE: Nebulization during inspiration can be accomplished only by a nebulizer control that is built into the ventilator.) Continuous nebulization is recommended in patients with status asthmaticus.

Technical Problems Associated With Continuous Nebulization Using an External Gas Source

Several problems are associated with adding a nebulizer to a patient circuit. Because the external nebulizer is powered by a continuous external gas source, ventilator function is affected. This is particularly true of the microprocessor ventilators that rely on the monitoring of exhaled gas flows and pressures. For example, expiratory monitors will display higher flows and volumes from previous settings because they will detect the added gas flow from the flowmeter powering the SVN. The high volumes may cause activation of volume alarms that were set when mechanical ventilation was initiated.

When the expiratory valve closes to deliver a positive pressure breath, the added flow increases volume and pressure delivery within the circuit and the patient. This added volume and pressure could be quite significant in infants.[81]

Preset ventilator variables may need to be adjusted during the treatment. In any patient-triggered mode, the patient must inhale (overcome) the flow added to the circuit by the external source to trigger the ventilator. As a result, patients with weak inspiratory efforts may be unable to trigger a machine breath.[82] The apnea alarm will not activate because the expiratory flow monitors detect the flow from the external gas source. Using an external gas source can also alter the F_IO_2 delivery to the patient.

Medications that pass through the expiratory valve and flow measuring devices may "gum up" these devices, thereby changing their functions. An expiratory gas filter can be used to prevent accumulation of aerosolized medications on the expiratory valves and monitors. However, these filters should be used with caution because as drugs accumulate on the filter, they can increase expiratory resistance and contribute to the generation of auto-PEEP. (NOTE: It is also important to recognize that the increased resistance detected may be the result of a "clogged" expiratory filter rather than from an increase in the patient's R_{aw}.) It may be necessary to change the low-V_T alarm settings, the low $\dot{V}_E$ alarm settings, and the sensitivity setting when adding an external nebulizer so that ventilation is guaranteed during treatment. The clinician must remember to change them back after the treatment is completed.

The use of expiratory filters during mechanical ventilation can reduce exposure of the staff to the aerosols emanating through the ventilator's expiratory filter and into the environment. (Risk for exposure to second hand or exhaled aerosol can account for more than 45% of the medication dose administered in addition to droplet nuclei produced by the patient.) Use of ventilators without expiratory filters increases the risk for exposure to aerosol released to the atmosphere from the ventilator, which increases the risk for second-hand exposure for caregivers and families. Without an expiratory filter, aerosol released from the ventilator is more than 160-fold higher than when an expiratory filter is added.[83,84]

Inline SVNs can become contaminated with bacteria and increase the risk for nosocomial infection because these contaminated aerosol particles can be delivered directly into the patient's respiratory tract. The CDC recommends cleaning nebulizers before every treatment. Nebulizers should be removed from the circuit after each use, disassembled, rinsed with sterile water (if rinsing is needed), air-dried, and stored aseptically.[34]

Nebulization Provided by the Ventilator

Several microprocessor-controlled ventilators are equipped with nebulizer-powering systems. It is important to recognize that these ventilators differ in their ability to power nebulizers. Some ventilators power the nebulizer only during mandatory breaths on inspiration, whereas other ventilators can power the nebulizer only when inspiratory gas flow is greater than a certain value (e.g., >10 L/min gas flow from the ventilator). In some ventilators the duration of nebulizer flow also changes with the inspiratory flow waveform selected. In still others, each breath triggers nebulizer flow, whether mandatory or spontaneous.

Delivery of the aerosol by the ventilator is greater when the pressure powering the nebulizer is 3.5 to 8.5 pounds-per-square-inch gauge (psig).[67] The clinician must be familiar with the ventilator used to know which ventilator modes can be used with a nebulizer and the unit's flow requirements and capabilities. Sophisticated algorithms in the software of current ICU ventilators maintain the F_IO_2 and the V_T delivery so that these settings are not altered when the ventilator's nebulizer system is activated.

A growing trend is the use of USNs and VMN devices during mechanical ventilation. These devices produce particles in the approximate range of 5 to 10 μm. In addition, they do not require a separate gas source because they are electrically powered. Consequently, these devices do not alter volume delivery or O_2 delivery. By comparison, pMDIs, VMNs, and USNs are more efficient than SVNs. For example, mean inhaled percent dose is two to four times greater with a VMN than an SVN. However, note that when bias flow is present, an SVN or VMN positioned proximal to the ventilator (before the humidifier) delivers more aerosol than when placed at the Y-piece.[85]

The Aeroneb Pro and Aeroneb Solo (Aerogen, Inc., Galway, Ireland) use vibrating mesh technology and can be connected to a variety of mechanical ventilators. The aerosol particle characteristics are similar to those of a USN. An example of a ventilator that uses a small-volume USN is the Servo-i ventilator (Fig. 12.8). Undiluted medication can be injected directly through a membrane at the top of the device, so the nebulizer does not have to be opened to accomplish filling. The mass median diameter of particles produced by the nebulizer is 4.0 μm. The operator sets the amount of time desired for nebulization on the ventilator, and nebulization is administered continuously. Other small-volume USNs are also available for mechanical ventilators. See Box 12.8 for protocol for using nebulizers for drug administration.

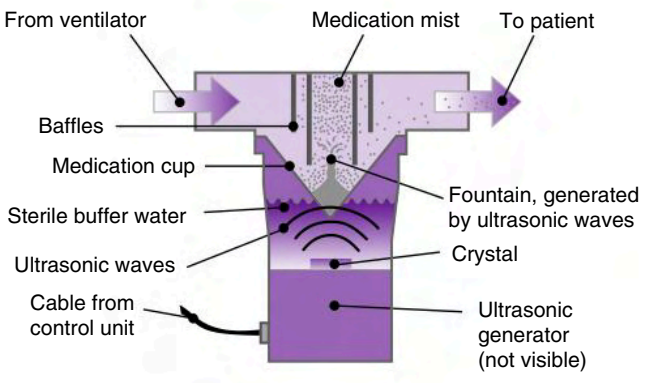


Fig. 12.8 A small-volume ultrasonic nebulizer designed for use with a mechanical ventilator. A vibrating piezoceramic crystal generates ultrasonic waves that pass through the couplant (sterile buffer water) and the medication cup to produce a standing wave of medication, which produces aerosol particles. (Courtesy Aerogen, Inc, Galway, Ireland; http://www.aerogen.com.)

BOX 12.8 Protocol for the Administration of Medications With Nebulizers During Mechanical Ventilation

The following procedure is recommended when administering aerosols to patients on mechanical ventilation with a small-volume nebulizer (SVN), ultrasonic nebulizer (USN), or vibrating mesh nebulizer (VMN):

1. Review the order, identify the patient, and assess the need for bronchodilator. (Suction airway if needed.)
2. Establish the dose required to compensate for decreased delivery (possibly 2–5 times the normal dose for a spontaneous patient when using an SVN).
3. Place the prescribed amount of drug in the nebulizer and add diluent to an optimum fill volume.
4. Place the SVN proximal to the humidifier and the USN and VMN in the inspiratory line about 15 cm (6 in.). from the Y-connector. Check to ensure the circuit has no leaks.
5. If possible, turn off bias flow or flow trigger that produces a continuous flow through the circuit during exhalation while nebulization is proceeding.
6. Remove the heat–moisture exchanger (HME) from the circuit
7. Turn on the USN or VMN, or set the gas flow to SVN at 6 to 8 L/min. (NOTE: Use the ventilator nebulizer system if it meets the SVN flow needs and cycles on inspiration; otherwise, use continuous flow from an external source.)
8. When possible, adjust the ventilator for optimum medication delivery (high V_T range, low *f* range, low flow range, long inspiratory time (T_I >0.3 s), while maintaining appropriate $\dot{V}_E$. (NOTE: Added flow from an external source will increase volume and pressure delivery.)
9. In the case of the SVN, adjust the low V_T and low $\dot{V}_E$ alarm, upper pressure limit, and sensitivity to compensate for added flow. With USN and VMN, no changes are required because they do not alter volume, flow, pressure, or O_2 delivery.
10. Check for adequate aerosol generation and manually tap nebulizer periodically during treatment until all medication is nebulized.
11. Monitor for any adverse response to administration of medication.
12. Remove SVN from the circuit, rinse with sterile water, air-dry, and store in safe place. USN and VMN might not require removal or rinsing. The manufacturer's recommendations should be followed with these two devices.
13. Replace the HME into the circuit.
14. Return ventilator settings to pretreatment values, if changed.
15. Return low V_T, low $\dot{V}_E$, upper pressure limit alarms, and sensitivity setting to original appropriate settings, if changed.
16. Evaluate and assess outcome and document findings.

Use of Nebulizers During Noninvasive Positive Pressure Ventilation

Several points should be mentioned regarding nebulization of medications during noninvasive positive pressure ventilation

(NIV). Preliminary studies suggest that both pMDI and SVN can be used to deliver bronchodilators during NIV. For the pMDI and SVN, the greatest aerosol deposition occurs when the nebulizer is placed close to the patient (between the leak port and the face mask), the inspiratory pressure is high (20 cm H_2O), and the expiratory pressure is low (5 cm H_2O).[62] Additional studies will be required to determine the optimum settings to be used with the USN and VMN during NIV.

Patient Response to Bronchodilator Therapy

Monitoring patient response to bronchodilators can be done by measuring lung mechanics (e.g., compliance, resistance, ventilating pressures), listening to breath sounds, evaluating vital signs and S_pO_2, and monitoring pressure-time curves, flow-volume loops, and pressure-volume loops. The following suggest an improvement after therapy:

- Reduced peak inspiratory pressure (PIP)
- Reduced transairway pressure (P_{TA})*
- Increase in peak expiratory flow rate (PEFR)
- Reduction in auto-PEEP levels (if present before beginning treatment)

Fig. 12.9 shows before and after flow-volume loops illustrating how both inspiratory and expiratory flow and volume delivery improve after bronchodilator therapy (Case Study 12.3).[86,87]

POSTURAL DRAINAGE AND CHEST PERCUSSION

Although suctioning remains the primary method of secretion clearance for patients with ETs in place, secretions in peripheral bronchi cannot be reached with this procedure. Postural drainage and chest percussions are other techniques that can be used to help clear airway secretions and improve the distribution of ventilation. In patients on ventilation, postural drainage involves placing the patient in a number of prescribed positions to drain the affected lung segment. Note that identifying the affected lung segments can be accomplished by analyzing chest radiographs and auscultation of the chest. This procedure is commonly accompanied by percussion of the chest wall using manual techniques or pneumatic percussors.

A study by Takahashi and associates[88] recommended the following positions for patients on ventilation based on their findings:

- Supine
- 45-degree rotation prone with left side up
- 45-degree rotation prone with right side up
- Return to supine
- Additional patient positions thought to be helpful include 10 degrees right-side-up supine and 45 degrees rotation prone with head raised 45 degrees

Positioning, particularly toward the prone position, is difficult in patients on mechanical ventilation and typically requires two or more clinicians to accomplish. Extreme care must be used when moving patients to avoid accidental extubation or loss, stretching, or kinking of catheters. Patient comfort and safety should always be a primary concern when working with critically ill patients. Because of the potential difficulties that can occur during postural drainage and chest percussions in patients with reduced cardiopulmonary reserve or ICP, other methods, such as use of an oscillating vest (Fig. 12.10), may provide alternative methods for secretion clearance. With the Vest Airway Clearance System (Hill-Rom, St. Paul, MN), chest wall vibrations are delivered to a vest

*$P_{TA} = PIP - P_{plat}$.

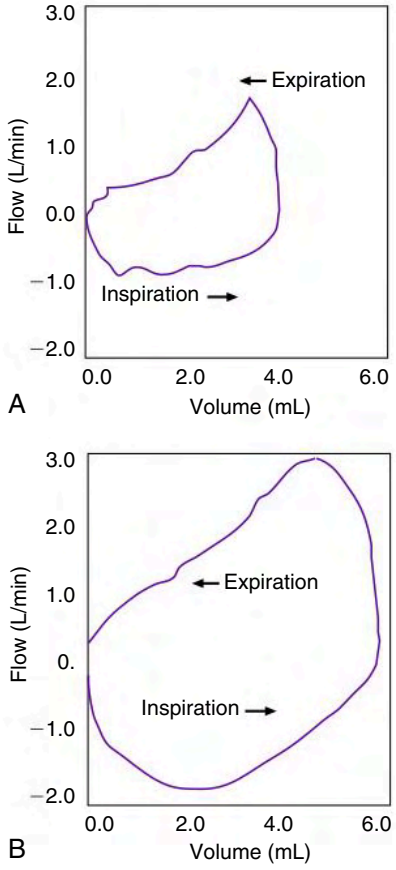


Fig. 12.9 These tidal flow—volume loops are based on mechanical breaths from an infant with a dramatic response to bronchodilator therapy during ventilation. (A) Before bronchodilator. (B) Twenty minutes after bronchodilator. Notice the increase in tidal volume and peak flows after bronchodilator administration. (From Holt WJ, Greenspan JS, Antunes MJ, et al.: Pulmonary response to an inhaled bronchodilator in chronically ventilated preterm infants with suspected airway reactivity, *Respir Care* 40:145—151, 1995.)

Case Study 12.3

Evaluation of Bronchodilator Therapy

After the administration of 2.5 mg of albuterol by SVN, the respiratory therapist evaluates preparameters and post-parameters and notes the following:

- Pretreatment: PIP = 28 cm H_2O, P_{plat} = 13 cm H_2O, P_{TA} = 15 cm H_2O
- PEFR = 35 L/min (measured from flow—volume loop)
- Post-treatment: PIP = 22 cm H_2O, P_{plat} = 15 cm H_2O, P_{TA} = 7 cm H_2O
- PEFR = 72 L/min
- Did the treatment reduce the patient's airway resistance?

Fig. 12.10 The Vest Airway Clearance System. (Manufacturer Advanced Respiratory, St. Paul, Minn.)

positioned around the patient's thorax. Vibrations are produced when pressure pulses generated by an air compressor are delivered through tubing to the vest. The pressure settings and frequency of oscillation are adjustable.

Although all the techniques discussed appear to be effective, additional studies are needed to compare the effectiveness of the various airway clearance methods in mechanically ventilated patients and better define potential complications associated with their use.

FLEXIBLE FIBEROPTIC BRONCHOSCOPY

Bronchoscopy is an invasive procedure used to visualize the upper and lower respiratory tract. It has become an important procedure for the diagnosis and treatment of various types of respiratory disorders, including inflammatory, infectious, and malignant diseases. It can be accomplished using either a flexible fiberoptic or rigid bronchoscope. The flexible fiberoptic bronchoscope consists of a long, flexible tube that contains three separate channels (Fig. 12.11), which are described as follows:

- A light-transmitting channel contains optical fibers that conduct light into the airway.
- A visualizing channel uses optical fibers to conduct an image of the airway to an eyepiece.
- An open multipurpose channel that can be used for aspiration, tissue sampling, or O_2 administration.

Bronchoscopy can be used to inspect the airways, remove objects from the airway, obtain biopsies of tissue and secretion samples, and clear secretions from the airway. Box 12.9 lists the indications and contraindications for fiberoptic bronchoscopy.[89] Newer fiberoptic bronchoscopes like the endobronchial ultrasound (EBUS-TBNA: Olympus, Center Valley, PA) allow the use of ultrasound technology to locate specific structures in the lungs and airways, such as lymph nodes, blood vessels, and abnormal structures (e.g., tumors). EBUS-TBNA allows sampling of lymph nodules with real-time view, potentially making lung biopsy less invasive and safer than conventional blind biopsy.

Another fiberoptic bronchoscope, the Electromagnetic Navigation Bronchoscope (superDimension, Inc., i-Logic System, Minneapolis, MN) incorporates a computed tomographic image that is reconfigured into a three-dimensional image. The image maps a navigational pathway through the airways to help locate lesions in lung tissue and mediastinal lymph nodes. The scope can navigate to the outer periphery of the lungs to perform a biopsy of suspicious findings in the lung fields.

Before beginning a bronchoscopy, the respiratory therapist should explain the procedure to the patient, gather the equipment and medications that will be needed, and administer preprocedure medications. An intravenous (IV) line is typically placed for the procedure to administer IV drugs for conscious sedation.

Atropine is sometimes administered 1 to 2 hours before the procedure to reduce secretion production and help dry the patient's airway so that it is easier to visualize. Atropine also blocks the vagal response (e.g., bradycardia and hypotension) that can occur when the bronchoscope enters the upper airway. Conscious sedation typically involves the use of agents such as:

- *Opioid analgesics:* Fentanyl citrate (Sublimaze), meperidine hydrochloride (Demerol), and hydromorphone hydrochloride (morphine)

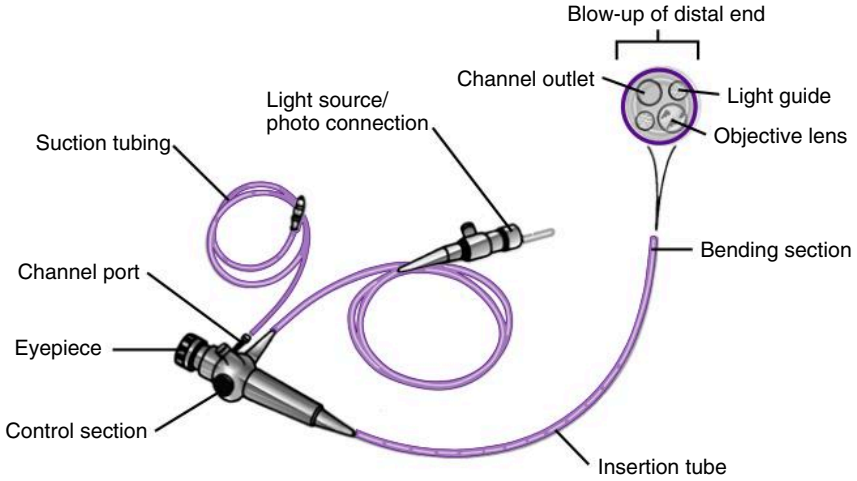


Fig. 12.11 Flexible fiberoptic bronchoscope. (See text for additional information.) (From Wilkins RL, Stoller JK, Kacmarek RM, editors: *Egan's fundamentals of respiratory care,* ed 9, St. Louis, MO, 2009, Mosby.)

BOX 12.9 Excerpts From the AARC Clinical Practice Guidelines for Bronchoscopy Assisting

Indications

- The presence of lesions of unknown cause on the chest radiograph or the need to evaluate persistent atelectasis or pulmonary infiltrates
- The need to assess upper airway patency or mechanical properties of the upper airways
- Suspicious or positive sputum cytology results
- The suspicion that secretions or mucus plugs are causing atelectasis

The need to:

- Obtain lower respiratory tract secretions, cell washings, or biopsy samples for evaluation
- Investigate hemoptysis, unexplained cough, wheeze, or stridor
- Evaluate endotracheal or tracheostomy tube problems
- Assist in performing difficult intubations
- Determine the location/extent of inhalation or aspiration injuries
- Remove abnormal tissue or foreign material
- Retrieve a foreign body
- Therapeutically manage ventilator-associated pneumonia
- Achieve selective intubation of a mainstem bronchus
- Place and/or assess airway stent function
- Perform airway balloon dilation in the treatment of tracheobronchial stenosis

Contraindications

Absolute Contraindications

- Absence of patient informed consent, unless a medical emergency exists and the patient is not competent
- Absence of an experienced bronchoscopist to perform or supervise the procedure
- Lack of adequate facilities and personnel to care for emergencies, such as cardiopulmonary arrest, pneumothorax, or bleeding
- Inability to adequately oxygenate the patient during the procedure

Perform Only If Benefit Outweighs Risk in Patients With the Following Disorders

- Coagulopathy or bleeding diathesis that cannot be corrected
- Severe obstructive airways disease
- Refractory hypoxemia
- Unstable hemodynamic status including arrhythmias

Relative Contraindications (Recognize Increased Risk)

- Lack of patient cooperation
- Recent myocardial infarction/unstable angina
- Partial tracheal obstruction
- Moderate to severe hypoxemia or any degree of hypercarbia
- Uremia and pulmonary hypertension
- Lung abscess
- Obstruction of the superior vena cava
- Debility, advanced age, and/or malnutrition
- Disorders requiring laser therapy, biopsy of lesions obstructing large airways, or multiple transbronchial lung biopsies
- Known or suspected pregnancy (safety concerns of possible radiation exposure)

Hazards and Complications

- Adverse reaction to medications used before and during the bronchoscopic procedure
- Hypoxemia
- Hypercarbia
- Bronchospasm
- Hypotension
- Laryngospasm, bradycardia, or other vagally mediated phenomena
- Epistaxis, pneumonia, and hemoptysis
- Increased airway resistance
- Infection hazard for health care workers or other patients
- Cross contamination of specimens or bronchoscopes
- Nausea and vomiting
- Fever and chills
- Cardiac dysrhythmias
- Death

Resources

Equipment

- Rigid or flexible fiberoptic bronchoscope
- Bronchoscopic light source and any related video or photographic equipment, if needed
- Specimen collection devices
- Syringes for medication delivery, normal saline lavage, and needle aspiration
- Bite block
- Laryngoscope
- Endotracheal tubes in various sizes
- Thoracotomy tray
- Adaptor with ability to connect mechanical ventilator and bronchoscope simultaneously
- Sterile gauze
- Water-soluble lubricant and lubricating jelly
- Laboratory requisition documentation

Monitoring Devices

- Pulse oximeter
- Electrocardiogram monitor
- Sphygmomanometer and stethoscope
- Whole-body radiation badge for personnel if fluoroscopy is used
- Capnograph

Procedure Room Equipment

- O_2 and related delivery devices
- Resuscitation equipment
- Medical vacuum system
- Fluoroscopy equipment, including personal protection devices, if warranted
- Adequate ventilation and other measures to prevent transmission of tuberculosis
- Decontamination area equipment
- Medications, including topical anesthetics, anticholinergic agents, sedatives, vasoconstrictor, nasal decongestants, and emergency and resuscitation drugs

Monitoring

Patient monitoring should be performed before, at regular intervals during, and after bronchoscopy until the patient meets appropriate discharge criteria. The level of monitoring required will be influenced by the level of sedation used during the procedure.

Infection Control

- Standard precautions should be used unless disease-specific precautions are required
- Centers for Disease Control and Prevention Guideline for Handwashing and Hospital Environmental Control, Section 2: Cleaning, Disinfecting, and Sterilizing Patient Care Equipment
- Hepatitis B vaccination for personnel

Modified from American Association for Respiratory Care Clinical Practice Guideline: bronchoscopy assisting, *Respir Care* 52:74–80, 2007.

- *Benzodiazepines:* Midazolam hydrochloride (Versed) or diazepam (Valium)

Narcotics depress the laryngeal cough reflex and alter the respiratory pattern to a slower and deeper pattern. Naloxone hydrochloride (Narcan) or flumazenil (Romazicon) should be available if reversal of the sedation is required. In ventilated patients some analgesics and sedatives may already be in use. Therefore obtaining a list of medications the patient is currently receiving is important.

Other useful information to obtain before the procedure includes thoracic imaging reports and laboratory data, particularly clotting factors. A discussion concerning performing the procedure on a spontaneously breathing patient is reviewed elsewhere and is beyond the scope of this text.[90]

Topical anesthesia to the upper airway, which is normally administered to spontaneous nonintubated patients, is usually not required when fiberoptic bronchoscopy is performed on intubated patients. A solution of 2% lidocaine is sometimes instilled into the ET to help reduce coughing when the bronchoscope is introduced.

Performing fiberoptic bronchoscopy generally requires three team members, including a physician, a respiratory therapist or pulmonary function technologist, and an individual trained in conscious sedation (nurse or respiratory therapist). The nurse typically manages drug administration and keeps records of the drugs used, O_2 saturation, and vital signs. The physician performs the bronchoscopy, and the respiratory therapist or pulmonary function technologist assists the physician by passing different instruments used for biopsy and specimen collection or suctioning the airway. The therapist is also responsible for monitoring the patient and ventilator.

In patients with artificial airways, choosing the appropriately sized fiberoptic bronchoscope is critical. Once the scope is inserted into the ET, it may occupy 50% or more of the radius of the ET. To help compensate for the tube obstruction, the F_IO_2 is increased to 1.0 during the procedure. To insert the scope, a special adapter like the one shown in Fig. 12.12 is placed between the Y-connector and the patient's ET connector. Once the scope is introduced, the decrease of the ET diameter causes the PIP to increase (during VC-CMV) and the delivered V_T to decrease as some leaking around the scope occurs. Auto-PEEP may occur as well. The respiratory therapist will typically have to adjust the ventilator, silence alarms, and monitor S_pO_2 and exhaled V_T during the procedure.[91]

Fig. 12.12 Photograph of an adapter used during fiberoptic bronchoscopy for patients on invasive mechanical ventilation. The adapter is placed between the Y-connector and the endotracheal tube.

ADDITIONAL PATIENT MANAGEMENT TECHNIQUES AND THERAPIES IN VENTILATED PATIENTS

Sputum and Upper Airway Infections

Patients on mechanical ventilation with artificial airways in place are at high risk for upper airway infections and VAP. Some of the causative agents for VAP are discussed in Chapter 14.

An elevated patient temperature with an increased white blood cell count (>10,000 cm^3) may be evidence of an infection. A sputum specimen should be collected and examined for color, quantity, and consistency and then sent to a laboratory for a culture and sensitivity and wet sputum analyses. Table 12.4 lists sputum color and characteristics that are associated with certain patient problems. Isolating and culturing an organism from the sputum or blood of an infected patient can indicate the causative microbe.

The evaluation of sputum can be correlated with other clinical data such as physical findings and radiographic reports to show a complete picture of a patient's condition in relation to a pulmonary infection. Physical findings might include the presence of crackles, dullness to percussion on physical examination, and purulent sputum. The chest radiograph of an infected patient will typically show evidence of a new or progressive infiltrate, consolidation, cavitation, or pleural effusion, any of which may be consistent with the presence of pneumonia.[92,93]

TABLE 12.4 Sputum Color and Possible Associated Problems

Sputum Color	Potential Problem
Yellow	Suggests the presence of pus (white blood cells) and possible infection
Green, thick	Suggests that sputum has been in the airway for a while because the breakdown of mucopolysaccharides (a component of sputum) results in a green color
Green, foul-smelling	Occurs with *Pseudomonas* infection
Pink-tinged	May indicate fresh blood or can occur after treatment with aerosolized epinephrine, isoproterenol, racemic epinephrine, or isoetharine
Fresh blood present	Suggests airway trauma, pneumonia, pulmonary infarction, or emboli
Brown	Usually indicates old blood
Rust	Might indicate a *Klebsiella* infection
Pink, copious, and frothy	Indicates pulmonary edema

FLUID BALANCE

Positive pressure ventilation can affect fluid balance and urine output, so it is important to monitor fluid input and output. This can be done by comparing daily fluid intake with output (i.e., urine output) and measuring body weight daily. This information can be used to alert the medical staff of significant changes in a patient's fluid balance.

Normal urine production is about 50 to 60 mL/h (approximately 1 mL/kg/h). Oliguria is a urine output of less than 400 mL/day or less than 20 mL/h. Polyuria is a urine output of more than 2400 mL/day or 100 mL/h.[94]

Decreases in urine output during mechanical ventilation can be caused by any of the following:

- Decreased fluid intake and low plasma volume
- Decreased cardiac output resulting from decreased venous return, increased levels of plasma antidiuretic hormone (ADH), heart failure, or relative hypovolemia (dehydration, shock, hemorrhage)
- Decreased renal perfusion
- Renal malfunction
- Postrenal problems such as obstruction or extravasation of urinary flow from the urethra, bladder, ureters, or pelvis
- A blocked Foley catheter (one of the most common causes of sudden drops in urine flow, which can be quickly reversed by irrigating the catheter)

Laboratory evaluation of acute renal failure includes tests of blood urea nitrogen (BUN), serum creatinine, ratio of BUN to serum creatinine, serum and urine electrolytes, urine creatinine, and glomerular filtration rate. An increase in body weight that is not associated with increased food intake is typically caused by fluid retention. When urine production is reduced and body weight is increased, the cause must be identified and corrected.

Changes in fluid balance may also affect blood cell counts. Fluid retention (overhydration) causes a dilution effect (hemodilution), leading to reduced hemoglobin, hematocrit, and cell counts. Dehydration can cause hemoconcentration and falsely high readings of these same variables.

For a patient receiving positive pressure ventilation, high mean airway pressures (P_{aw}) can lead to decreased cardiac output and increased plasma ADH. When this occurs, attempts to decrease P_{aw} should be made. Pulmonary artery pressure (PAP) monitoring is valuable in this situation. If cardiac output increases when P_{aw} is decreased, alterations in fluid balance may be the result of positive pressure ventilation.

Relative hypovolemia can be caused by dehydration, shock, or hemorrhage. Clinically it causes low vascular pressures (low PAP, low central venous pressure [CVP], and low pulmonary artery occlusion pressure [PAOP]). (See Chapter 11 for additional information on hemodynamic monitoring.) Dehydration commonly results from inadequate fluid intake, vomiting, or diarrhea. It can also be caused by fluid shifting from the plasma to the interstitial space.

Dehydration or relative hypovolemia is evaluated by giving fluid challenges until adequate BP values are restored. Shock is usually treated with fluid administration and appropriate medications, such as dopamine, phenylephrine, norepinephrine, or metaraminol, any of which may help increase BP (Case Study 12.4).

If cardiac output and urine output are decreased and PAOP is increased, failure of the left side of the heart should be suspected. Chronic failure of the left side of the heart also increases PAP and CVP and is treated with drugs such as digitalis (to increase contractility and cardiac output) and morphine (to decrease venous return to the heart), diuretics (to unload excess fluids through the kidneys), and O_2 (to improve myocardial oxygenation). Sodium nitroprusside can be used to dilate both arterial and venous vessels, which reduces preload (venous return and end-diastolic volume) and afterload (peripheral vascular resistance). However, the use of this agent must be monitored carefully because of its effects on vascular pressures (i.e., PAOP, PAP, and BP).

Case Study 12.4

Evaluating Fluid Status

A patient receiving mechanical ventilatory support has elevated red and white blood cell counts. Skin turgor is decreased; urine output has been averaging 40 mL/h; and blood pressure has been lower than the patient's normal value. What is the most likely problem and what would you recommend?

Renal failure or malfunction is another common cause of decreased urine production in critically ill patients. Severe hypoxemia, sepsis, and other clinical problems can lead to renal malfunction. The urine is checked for the presence of blood cells and elevated protein or glucose levels, as well as for its specific gravity, color, and amount. The presence of abnormal substances in the urine and abnormal BUN levels are indicative of renal malfunction.

Excessive fluid intake can also result from iatrogenic causes. An IV line may malfunction and cause fluids to be administered too rapidly. Another factor often overlooked regarding fluid intake and output in patients receiving mechanical ventilation is to account for the water associated with high humidity from heated humidifiers. This additional fluid may represent a considerable portion of a patient's fluid intake, particularly in neonates and infants.

PSYCHOLOGICAL AND SLEEP STATUS

As patients regain consciousness while on ventilatory support, it is important to show encouragement and explain to them why the ventilator and ET are being used. It is also important to demonstrate to the patient how to communicate his or her needs. Patients should have confidence in the personnel who care for them. Whenever an alarm sounds, the clinician should check the patient first and then check the equipment. It can be comforting to a patient to have the clinician explain that all is well and that he or she need not be concerned about the alarm.

Critically ill patients typically demonstrate a certain level of sleep disturbance secondary to factors such as pain, medications, staff interruptions, noise, and light. The level of sleep disturbance or sleep fragmentation in patients on mechanical ventilation is similar to that seen in patients with obstructive sleep apnea who have impaired cognitive function and excessive daytime sleepiness.[95]

Relatively little information is available about the relation between patient–ventilator interaction and sleep. In one study, the

ventilator mode was noted to alter sleep function in some patients. PSV used during sleep was thought to induce frequent periods of apnea (central apnea) compared with VC-CMV, which has a set minimum rate. These apneic periods were attributed to longer T_I, deeper V_T, and the subsequent transient lowering of P_aCO_2 values (hypocapnia). In this study, the decreased P_aCO_2 reduced the drive to breathe and the patient then experienced sleep apnea and sleep disturbance. During the apneic periods, the P_aCO_2 rose to 7 mm Hg above wakeful state P_aCO_2. The apneic periods were also associated with frequent patient arousals from sleep. Repeated arousals can elevate catecholamine levels and BP and contribute to cardiac arrhythmias and cardiac failure.[95] Practitioners are cautioned against misinterpreting the periods of hypercapnia during sleep in patients receiving ventilation with PSV.

Patients in the ICU who are deprived of sleep and given a variety of drugs can have many psychological problems. It is not unusual for them to become combative, restless, anxious, depressed, frustrated, and angry and even experience hallucinations. Fortunately, many patients cannot later recall the time they spent in the ICU. The staff must understand that patients may respond in unusual or atypical ways; it is important to explain this to family members. Whenever possible, allow patients to rest and sleep undisturbed and give them as much privacy as possible, a concept that is often not practiced in many ICUs.

Members of the health care team should be respectful, kind, and reassuring and keep a positive attitude at all times around the patients for whom they are caring. They should abide by patient confidentiality requirements and protect patients' private information. Being emotionally supportive of patients is vitally important. Addressing patients' psychological needs can be as important as ensuring that their physical needs are met.

PATIENT SAFETY AND COMFORT

Practitioners should always keep in mind the primary reasons for initiating ventilatory support. Patients receiving short-term mechanical ventilation include postoperative patients and those with an uncomplicated drug overdose. Patients who may require longer periods of mechanical ventilation (e.g., several days to 1–2 weeks) include posttrauma victims and patients with asthma, COPD, pulmonary edema, aspiration, and ARDS. Patients who may require 2 or more weeks of ventilator support typically include those with severe COPD, neuromuscular disorders such as myasthenia gravis, Guillain-Barré, tetanus, botulism, cerebrovascular accidents, and cranial tumors and those being treated for neurosurgical problems.

Patient Safety

To be ready for emergency situations, clinicians should always make sure that a manual resuscitator with mask, an O_2 source, intubation equipment, an emergency tracheostomy kit, a thoracentesis tray, suction equipment, an emergency cart stocked with the appropriate emergency medication, and an ABG kit are accessible. Emergency equipment that is readily accessible can provide immediate patient care and protect patient safety.

Staff should rely on keen observation and early detection of problems in both patients and mechanical equipment to ensure patient safety and comfort. The patient-ventilator system should be monitored at regular intervals. It is important to try to anticipate problems and trust the assessments made with your senses because the information obtained from monitors may not accurately reflect a patient's true condition or level of comfort.

Patient Comfort

A patient receiving ventilatory support may experience physical discomfort caused by pain from trauma or disease, an awkward body position, distended organs, inadequate ventilation, heavy tubing, restraints, limb boards, the inability to talk or swallow, coughing or yawning, poor oral hygiene, and overcooling or overheating because of environmental conditions. Every effort must be made to keep patients as comfortable as possible.

Feelings of confusion and delirium often occur in patients in the ICU.[3] Imagine the sense of vulnerability and isolation that patients on mechanical ventilation feel while in the ICU. They cannot talk, they are not surrounded by familiar family faces, and they are not sure when someone will return to their bedside or what health care providers will do when they return.

A major problem in many ICUs is the lack of effective methods of communicating with patients. Physicians and other caregivers are often in a hurry to move on to other tasks.[3] If it becomes difficult to communicate with a patient who has a tube in his or her mouth, all too often the caregiver gives up in frustration and leaves the patient no better off emotionally than when the caregiver first walked into the room.

Patients may also suffer from shortness of breath or dyspnea. Restoring ABGs to normal and alleviating patient-ventilator asynchrony may not alleviate dyspnea. Some speculate that using a low V_T for ventilation is associated with discomfort. It may be fair to assume that any volume that is different from what the patient desires produces discomfort and shortness of breath.[3] As an example, patients with muscular diseases seem to desire a large V_T that often results in low P_aCO_2 levels.

In a study involving reducing sedation in patients on mechanical ventilation in the ICU, researchers found that patients in the group who received continuous infusion of sedation remained awake for 9% of the time, whereas the group that had the sedation discontinued daily spent 85% of their time awake.[96] The decision to use sedatives in mechanically ventilated patients should be based on the patient's psychological and physiological condition. In many cases, the suggestion might be that it is better to be awake most of the time.

Another comment that is often made by clinicians is, "Patients who recover from respiratory failure should be thankful just to be alive. Most have little or no memory of their experience during mechanical ventilation anyway."[3] Several points can be made related to this comment:

- Most of us would not want to experience severe, sustained, and avoidable distress whether we remember it or not.
- Use of sedatives and analgesics needed to produce placidity and amnesia may be excessive and prolong the duration of ventilation and time in the ICU.[97]
- Long-term amnesia may not be as complete or protective as some believe. A high prevalence of anxiety disorders, depression, and posttraumatic stress disorder exists in survivors of ARDS.[97]
- Because of a significant lack of research in this area, little is known about the discomfort experienced by patients on ventilation.[3] What do patients receiving mechanical ventilation mean when they report shortness of breath?
- How often does dyspnea occur, and how severe is it under different circumstances of mechanical ventilation?

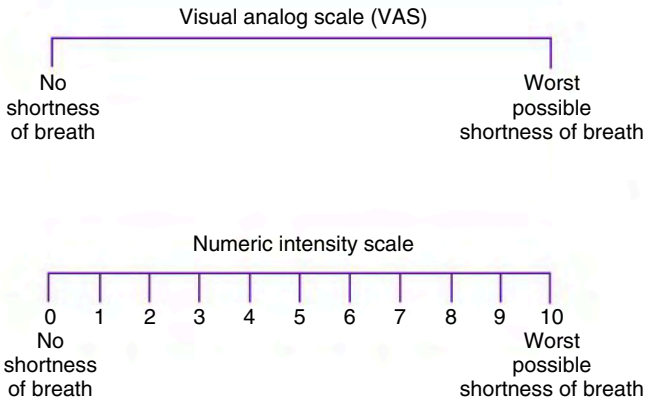


Fig. 12.13 Visual analog and numeric intensity scales. (From Hansen-Flaschen JH: Dyspnea in the ventilated patient: a call for patient-centered mechanical ventilation, *Respir Care* 45:1460—1464, 2000.)

- Can we adjust the ventilator to minimize patient dyspnea and reduce the need for sedation and analgesia?
- Can the incidence or severity of posttraumatic stress disorder be reduced in survivors by minimizing respiratory distress during ventilation?

It has been suggested that a patient's level of dyspnea during mechanical ventilation can be gauged using a visual analog or numeric intensity scale (Fig. 12.13).[98-100] A similar scale, the modified Borg scale, is widely used to measure dyspnea during exercise testing. Dyspnea scores do not correlate with physiological variables.[100] It is important to recognize that clinicians cannot always assume a patient is comfortable just because the laboratory results look good. Dyspnea must be measured more objectively using tools such as those mentioned.

Patient-Centered Mechanical Ventilation

Patient-centered mechanical ventilation should be directed toward improving patient safety and survival while simultaneously reducing patient distress and fear.[3] Patient comfort should be assessed at regularly scheduled intervals, such as when a patient-ventilator system check is performed. Several questions that the clinician can ask patients who are able to respond might include:

1. "Are you short of breath right now?" If the patient indicates that he or she is feeling short of breath, then,
2. "Is your shortness of breath mild (#1), moderate (#2), or severe (#3)?" (indicated by holding up fingers)

The clinician may be able to improve patient comfort by adjusting the ventilator flow rate or flow waveform, sensitivity level, pressure target, rise time percentage, and flow cycle criteria (in PSV) or switching modes. As changes are made, the patient can be asked whether one setting is more comfortable than another. When setting changes are completed, the clinician should check S_pO_2, $EtCO_2$, ABGs, ventilator graphics, and breath sounds to verify that new settings are not resulting in undesirable changes in physiological parameters. If the clinician is unable to improve the patient's comfort level, he or she should communicate with the patient's nurse to determine whether alternative therapies are available. Respiratory therapists are generally successful in complying with this type of dyspnea evaluation protocol.[98] More research is required in the area of assessing dyspnea and comfort levels in mechanically ventilated patients because limited information is currently available.

TRANSPORT OF MECHANICALLY VENTILATED PATIENTS WITHIN AN ACUTE CARE FACILITY

Transporting a seriously ill patient on mechanical ventilation is often required to move the patient from the ICU to a diagnostic or therapeutic area of the hospital. The average duration of patient transport (one way) is between 5 and 40 minutes, and the average time spent at the destination is 35 minutes.[101]

Every effort must be made to ensure the patient's condition remains stable. This often means continuing the use of medications, which requires transporting vascular lines and pumps. Catheters that may be attached to the patient, including Foley catheters, pleural drainage systems, cardiac and hemodynamic lines, and monitors, will need to be transported. The ventilator, a manual resuscitator and mask, and a reliable O_2 source must also be transported. Box 12.10 lists some of the equipment used during

BOX 12.10 Patient Support Equipment and Monitoring Equipment for Transport of the Ventilated Patient

Equipment
- Emergency airway management supplies
- Stethoscope (for breath sounds and blood pressure)
- Self-inflating manual resuscitator and mask (appropriate size)

Monitors
- Pulse oximeter
- Electrocardiogram and heart rate monitor and minimum of one channel vascular pressure measurement (a sphygmomanometer should be available if an invasive line and monitor are not present)
- Handheld spirometer for V_T monitoring (respiratory rate should be periodically monitored)

Transport Ventilator

If a ventilator capable of transport is used, it should have the following:
- Sufficient portable power (battery and gas) for the duration of transport
- Independent control of V_T and rate (V_T delivery should be consistent regardless of changing lung compliance or airway resistance)
- Continuous mandatory ventilation or intermittent mandatory ventilation mode capability
- Positive end-expiratory pressure capabilities
- Disconnect alarm, high-pressure alarm, and low-power (battery) alarm
- Pressure-monitoring capabilities
- Provide F_IO_2 (up to 100%)

From American Association for Respiratory Care Clinical Practice Guideline: In-hospital transport of the mechanically ventilated patient—2002 revision & update, *Respir Care* 47:721—723, 2002.

BOX 12.11 Excerpts From the American Association for Respiratory Care (AARC) Clinical Practice Guidelines for Contraindications, Hazards, and Complications of In-Hospital Transport of the Mechanically Ventilated Patient

Contraindications

Transport should not be undertaken unless all the essential personnel constituting the transport team are present.

Contraindications include the inability to do the following:

- Provide adequate oxygenation and ventilation during transport by manual resuscitation bag, portable ventilator, or standard intensive care unit ventilator.
- Maintain acceptable hemodynamic stability during transport.
- Monitor the patient's cardiopulmonary status during transport.
- Maintain a patent airway during transport.

Hazards and Complications

- Hyperventilation during manual ventilation, which may result in respiratory alkalosis, cardiac arrhythmias, and hypotension
- Loss of positive end-expiratory pressure/continuous positive airway pressure leading to hypoxemia or shock
- Position changes leading to hypotension, hypercarbia, and hypoxemia
- Tachycardia and other arrhythmias
- Equipment failure resulting in inaccurate data, loss of data, and loss of monitoring capabilities
- Accidental disconnection of intravenous access for drug administration resulting in hemodynamic instability
- Disconnection from ventilatory support and respiratory compromise resulting from movement
- Accidental extubation
- Accidental removal of vascular access
- Loss of O_2 supply leading to hypoxemia
- Ventilator-associated pneumonia resulting from transport

From AARC Clinical Practice Guideline: In-hospital transport of the mechanically ventilated patient—2002 Revision & Update, *Respir Care* 47:721–723, 2002.

transport of a seriously ill patient.[102] Because of all the equipment and personnel involved, transportation should be undertaken only if the benefits outweigh the risks.[103]

Box 12.11 lists the contraindications, hazards, and complications associated with in-hospital patient transport.[102] Available literature on in-hospital transport of patients on ventilation suggests that as many as two thirds of transports performed fail to yield results from diagnostic studies that would have affected patient care.[104]

Three options are available for providing ventilation during transport.

1. Manual ventilation with a self-inflating bag. This option has several risks, including inappropriate ventilation of the patient and contamination of the airway.
2. Use of a transport ventilator designed specifically for that purpose. Sophisticated microprocessor-controlled transport ventilators are small, lightweight, and easy to use.
3. Most current-generation ICU ventilators can be used for transport. These units are usually large, but most are equipped with backup battery power to maintain function of flow-control valves, displays, alarms, microprocessor systems, and monitors. These ventilators usually require pneumatic power. During transport, these units can operate with cylinder air and O_2.

Electrically powered transport ventilators rely on battery power during the transport procedure and then plug back into an AC outlet when an outlet is available. The battery power must be checked before beginning the transport process. Battery duration differs considerably among ventilators and may be shorter than that reported in the operator's manual. Clinicians need to be aware that portable ventilator battery life is affected by control settings, lung characteristics, and portable ventilator characteristics.[102] For example, the ventilator settings have an important effect on battery duration. The use of PEEP and pressure-controlled ventilation have the greatest effect on how long the battery will last in electrically powered transport ventilators.[102]

Having the ability to maintain the same V_T delivery during VC-CMV ventilation is another important characteristic of transport ventilators. Of the ventilators tested in one study, most maintained the V_T through the terminal battery testing. At least one reported model did not.[102] Clinicians should evaluate any ventilator by simulating transport conditions before they actually use a machine to transport a patient.

A major disadvantage of pneumatically powered ventilators is that they can consume large volumes of O_2 during operation. It is difficult to determine how long a cylinder of O_2 will last, because gas utilization depends on the O_2 setting, $\dot{V}_E$ requirements, lung mechanics, and operating characteristics of the ventilator. Transporting a patient receiving noninvasive ventilation may be difficult or impossible because leaks are typically present with these devices and ventilator gas consumption will be high as a result.

Ventilator selection and assembly, preparation of equipment, and personnel training and cooperation are all essential elements in the transport of patients within the acute care facility.

SUMMARY

- V_T and frequency adjustments should be based on the patient's pulmonary condition. Clinicians typically use V_Ts in a range of 6 to 8 mL/kg while maintaining the P_{plat} at less than 30 cm H_2O. Breathing frequencies of 12 to 18 breaths/min are typically acceptable.
- Treatment of metabolic acidosis and alkalosis should focus on identifying metabolic factors that can cause these acid-base disturbances.
- Permissive hypercapnia is a ventilator technique in which ventilatory support is limited to avoid lung overdistention and injury of the lung. During permissive hypercapnia, arterial partial pressure of carbon dioxide (P_aCO_2) values are allowed to rise above normal (e.g., $\geq$50), and pH values are allowed to fall below normal (e.g., $\geq$7.10 to $\leq$7.30).

- The use of permissive hypercapnia is restricted to situations in which the target airway pressure is at its maximum and the highest possible rates are being used.
- Clearing secretions from the ET or TT of mechanically ventilated patients is an important component of bronchial hygiene therapy. Suctioning at fixed intervals is not appropriate and should be performed only on the basis of patient assessment findings.
- Two methods of endotracheal suctioning can be performed on the basis of the type of catheter used: the open-circuit technique and closed-circuit technique. The duration of suctioning should be brief and must not exceed 15 seconds, and shallow suctioning is recommended over deep suctioning to avoid trauma to the lung.
- There is insufficient evidence to support the practice of instilling normal saline into the ET before suctioning.
- The most common devices used for administering aerosol are (pMDIs) and SVNs. USNs and vibrating mesh nebulizers (VMNs) are becoming more widely used. The primary advantage of using USNs and VMNs is that these devices produce smaller aerosol particles without the addition of gas into the ventilator circuit.
- Although pMDIs and SVNs are most often used to deliver bronchodilators and corticosteroids, only SVNs, USNs, and VMNs are used to deliver mucolytics, antibiotics, prostaglandins, and surfactants.
- Numerous ventilator-associated factors can affect the delivery of aerosols, including the mode of ventilation used, V_T and f, T_I, and inspiratory waveform.
- Bronchoscopy has become an important procedure for the diagnosis and treatment of various types of respiratory disorders, including inflammatory, infectious, and malignant diseases.
- A number of routine procedures should be used to ensure that the patient is comfortable and safe during mechanical ventilation.
- Patients on mechanical ventilation with artificial airways in place are at high risk for upper airway infections and VAP.

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

1. A patient on PC-IMV with no PEEP has the following ventilatory parameters and ABGs: set pressure = 20 cm H_2O; V_T = 400 mL; set rate = 8 breaths/min; spontaneous f = 25 breaths/min; spontaneous V_T = 225 mL; F_IO_2 = 0.4; P_aCO_2 = 58 mm Hg; pH = 7.28; and P_aO_2 = 89 mm Hg. The patient is at IBW of 140 lb (64 kg).
   A. Estimate the patient's total alveolar ventilation (assuming that the dead space changes associated with the ET and V_{Dmech} balance each other).
   B. Calculate the patient's C_S (assuming that flow drops to zero before end inspiration).
   C. On the basis of ABG results and ventilator data, how do you interpret these data, and what change(s) do you recommend?

2. A 67-year-old man with COPD is receiving mechanical ventilation with the following settings: V_T = 425 mL (6 mL/kg IBW), f = 6 breaths/min on IMV, F_IO_2 = 0.24. He has a spontaneous f of 25 breaths/min and a spontaneous V_T of 200 mL. PIP = 30 cm H_2O and P_{plat} = 22 cm H_2O. The following ABGs are obtained: pH = 7.25; P_aCO_2 = 89 mm Hg; P_aO_2 = 55; and HCO_3^- = 38 mEq/L. This patient has a normal P_aCO_2 of 55 mm Hg. What changes would you recommend?

3. A 45-year-old man with Pickwickian syndrome who is 5-ft, 4-in tall and weighs 280 lb (127 kg) is placed on mechanical ventilatory support after hip replacement surgery. The initial parameters are as follows: V_T = 1000 mL, f = 9 breaths/min, PIP = 50 cm H_2O, P_{plat} = 35 cm H_2O. ABGs show pH = 7.41, P_aCO_2 = 39 mm Hg, P_aO_2 = 120, HCO_3^- = 24 mEq/L, and F_IO_2 = 0.3. What changes would you recommend?

4. A 22-year-old comatose, apneic man with a closed head injury is on mechanical ventilation. He is also being medically treated for increased ICP. V_T = 600 mL (7.5 mL/kg), mode = VC-CMV, f = 14 breaths/min, no spontaneous efforts, P_aCO_2 = 40 mm Hg, pH = 7.39, P_aO_2 = 80 mm Hg on 0.25 F_IO_2. Which of the following changes would be most appropriate?
   A. Make no change at this time.
   B. Increase f to 18 breaths/min.
   C. Increase V_T to 1000 mL (about 12.5 mL/kg).
   D. Switch to the IMV mode of ventilation.

5. A 35-year-old woman with a size 9 ET requires suctioning.
   A. What is an appropriate suction catheter size?
   B. How long should the catheter be?
   C. What is an appropriate suction pressure?

6. Closed-suction catheters may be more appropriate than using open suctioning because of which of the following?
   A. They are less expensive.
   B. They reduce the risk for infections.
   C. There is no risk for catheter migration into the ET.
   D. The catheter adds no additional weight to the ventilator circuit.

7. The procedure of instilling normal saline into the ET before suctioning is known to do which of the following?
   A. Effectively thin secretions
   B. Pose no risk to the patient
   C. Increase an elderly patient's sensation of dyspnea
   D. Require a physician's order

8. Silent aspiration and VAP can occur with cuffed ETs as a result of which of the following?
   1. Injury to the mucosa during insertion and manipulation of the tube after insertion
   2. Interference with the normal cough reflex
   3. Aspiration of contaminated secretions that pool above the ET cuff
   4. Rupture of the ET cuff
      A. 1 and 2 only
      B. 1 and 4 only
      C. 1, 2, and 3 only
      D. 1, 2, and 4 only

9. Which of the following is true regarding the special ET that provides continuous aspiration of subglottic secretions?
   A. A pressure of 20 mm Hg is applied continuously to the suction lumen.
   B. The suction port is located just below the cuff on the dorsal side of the tube.

C. It is most effective in patients requiring intubation for less than 1 to 2 days.
D. It is no more expensive than a standard ET.

10. A 15-year-old patient with severe acute asthma is being mechanically ventilated. Which of the following methods will deliver the largest quantity of a β-agonist to the respiratory tract?
A. pMDI
B. pMDI with spacer
C. SVN
D. Dry powdered capsule

11. When delivering a medication by pMDI to a patient on mechanical ventilation, which of the following statements describes the best placement for the device?
A. Between the Y-connector and the ET using elbow connector
B. In the ventilator inspiratory limb proximal to the HME and the patient
C. On the expiratory limb at the Y-connector
D. In the ventilator circuit inspiratory limb at the Y-connector or between the elbow and the ET

12. Which of the following statements is *not* true when using an externally powered SVN placed in the ventilator circuit?
A. The added flow will alter monitoring of exhaled V_T and $\dot{V}_E$.
B. Patient inspiratory efforts may not be sufficient to trigger inspiratory flow from the ventilator.
C. Use of an expiratory filter may protect the expiratory valve and expiratory monitors from medication deposition.
D. The HME does not have to be removed from the circuit when using an SVN.

13. The use of atropine in patients who will be having a fiberoptic bronchoscopy is for the purpose of which of the following?
A. Calming the patient
B. Reducing respiratory rate and $\dot{V}_E$
C. Drying the airways
D. Helping the patient sleep

14. During fiberoptic bronchoscopy of mechanically ventilated patients, the respiratory therapist can anticipate what types of changes in ventilator function?
A. Increase in volume delivery
B. Increase in peak pressure
C. High-rate alarm
D. High minute volume alarm

15. Postural drainage positions recommended for mechanically ventilated patients include all but which of the following?
A. Supine
B. 45-degree rotation prone with left side up
C. 45-degree rotation prone with right side up
D. Seated

16. A patient on mechanical ventilation is suctioned for large amounts of foul-smelling green sputum. The patient has a temperature of 39° C and an elevated white blood cell count. The most likely cause of this problem is which of the following?
A. An overheated cascade humidifier
B. Cardiogenic pulmonary edema
C. An allergic reaction to acetylcysteine
D. A *Pseudomonas* infection

17. Patient-centered mechanical ventilation involves which of the following?
A. Looking at the patient first and not the machine when a ventilator alarm is activated
B. Involving the family in making ventilator changes
C. Asking the patient about his or her level of comfort and dyspnea when making ventilator changes
D. Involving all members of the health care team in patient management

18. Which of the following must be performed during patient transport to reduce the risk for complications?
A. Provide adequate oxygenation and ventilation during transport by manual resuscitation bag, portable ventilator, or standard ICU ventilator
B. Maintain acceptable hemodynamic stability during transport
C. Monitor the patient's cardiopulmonary status during transport
D. All of the above

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CHAPTER 13

Improving Oxygenation and Management of Acute Respiratory Distress Syndrome

OUTLINE

KEY TERMS

- Absorption atelectasis
- Cytokines
- Deflation point
- Deflection point
- Exudative
- Fibrosing alveolitis
- Independent lung ventilation
- Lower inflection point
- Prone positioning
- Recruitment maneuver
- Thrombotic mediators
- Upper inflection point

LEARNING OBJECTIVES

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

1. Calculate a desired F_IO_2 required to achieve a desired P_aO_2 on the basis of current ventilator settings and blood gases.
2. Calculate a patient's pulmonary shunt fraction.
3. Identify indications and contraindications for continuous positive airway pressure (CPAP) and positive end-expiratory pressure (PEEP).
4. List the primary goal of PEEP and the conditions in which high levels of PEEP are most often used.
5. Describe the most appropriate method for establishing an optimum level of PEEP for a patient with acute respiratory distress syndrome (ARDS) using a recruitment-derecruitment maneuver and the deflection point (lower inflection point during deflation or derecruitment).
6. Explain the effects of PEEP/CPAP therapy on a patient with a unilateral lung disease. Describe the problems associated with initiating PEEP in a patient with an untreated pneumothorax.
7. Recommend adjustments in PEEP and ventilator settings on the basis of the physical assessment of the patient, arterial blood gases (ABGs), and ventilator parameters.
8. Compare static compliance, hemodynamic data, and ABGs as indicators of an optimal PEEP.
9. Identify from patient assessment and ABGs when it is appropriate to change from CPAP to mechanical ventilation with PEEP.
10. Identify the severity of ARDS using the P_aO_2/F_IO_2 ratio.
11. Recommend an appropriate tidal volume (V_T) setting for a patient with ARDS.
12. Identify the maximum plateau pressure (P_{plat}) value to use for patients with ARDS.
13. Identify the criteria that should be used to liberate a patient from PEEP or CPAP.
14. Recommend a PEEP setting on the basis of the inflection point on the deflation curve using the pressure-volume loop for a patient with ARDS.
15. Describe the procedure for prone positioning in ventilated patients with ARDS.
16. List potential problems associated with placing the patient in a prone position during mechanical ventilation.
17. Discuss several theories that describe how prone positioning improves ventilation-perfusion in ARDS.

Improving the ventilatory status of a patient with hypercapnic respiratory failure (i.e., reducing the partial pressure of carbon dioxide [P_aCO_2]) can be accomplished by improving alveolar ventilation, reducing physiological dead space, and reducing carbon dioxide (CO_2) production. Improving oxygenation, on the other hand, involves using various patient management strategies, such as administering supplemental oxygen (O_2), applying positive end-expiratory pressure (PEEP) or continuous positive airway pressure (CPAP), and patient positioning.

Although the terms *hypoxia* and *hypoxemia* are often used interchangeably, it is important to recognize that *hypoxia* is defined as a reduction in O_2 in the tissues, whereas *hypoxemia* refers to a reduction in the partial pressure of O_2 in the blood (i.e., P_aO_2 <80 mm Hg and S_aO_2 <95%). Box 13.1 provides a brief description of the four types of hypoxia, and Key Point 13.1 provides P_aO_2 and S_aO_2 values typically used to identify mild, moderate, and severe hypoxemia.

The strategy used to treat hypoxia should focus on its cause. For example, hypoxemic hypoxia, which occurs when a person breathes rarefied air at a high altitude (i.e., reduced partial pressure of inspiratory O_2 [P_IO_2]) can be reversed by having the person breathe an enriched O_2 mixture. When hypoventilation causes hypoxemia, increasing minute ventilation generally improves oxygenation (Case Study 13.1). Serious anemia, on the other hand, is treated with the administration of blood products, which in turn

BOX 13.1 Types of Hypoxia

- Hypoxemic hypoxia (lower than normal P_aO_2, ascent to altitude, hypoventilation)
- Anemic hypoxia (lower than normal red blood cell count [anemia], abnormal hemoglobin, carbon monoxide poisoning)
- Circulatory hypoxia (reduced cardiac output, decreased tissue perfusion)
- Histotoxic hypoxia (cyanide poisoning)

Key Point 13.1

Levels of Hypoxemia[a]

Level	P_aO_2 Value (mm Hg)	P_aO_2 Range (mm Hg)	Saturation (S_aO_2) (%)
Mild hypoxemia	<80	60–79	90–94
Moderate hypoxemia	<60	40–59	75–89
Severe hypoxemia	<40	<40	<75

[a]Values given are for a young adult breathing room air. (NOTE: The levels of hypoxemia defined here may differ depending among clinicians and institutions.)

Case Study 13.1

Myasthenia Gravis

A patient with myasthenia gravis is placed on mechanical ventilation. The chest radiograph is normal. Breath sounds are clear. Initial arterial blood gases (ABGs) on 0.25 F_IO_2 20 minutes after beginning ventilation are as follows: pH = 7.31; P_aCO_2 = 62 mm Hg; bicarbonate = 31 mEq/L; and P_aO_2 = 58 mm Hg. What change in ventilator setting might improve this patient's ABG findings?

improves the patient's O_2-carrying capacity (i.e., hemoglobin). Circulatory hypoxia occurs when the patient's cardiac output is reduced. The treatment of this type of hypoxia typically involves fluid resuscitation and pharmacological interventions, which normalize the patient's cardiac output (e.g., administering drugs that increase ventricular contractility or decrease vascular resistance) and therefore improve O_2 delivery (DO_2) to the tissues. With histotoxic hypoxia, cyanide interferes with a person's ability to use O_2 to produce energy (cellular respiration) by uncoupling oxidative phosphorylation (i.e., cytochrome oxidase). Treatment of cyanide poisoning involves administering a cyanide antidote (e.g., hydroxocobalamin) and providing supportive care to maintain oxygenation and acid-base balance.

Improvement in oxygenation status may require time before the response to treatment is evident. This is particularly evident in cases involving hypoventilation, anemia, and circulatory hypoxia. In these cases, it is appropriate to administer supplemental O_2 until the hypoxemia is relieved.

This chapter begins with a discussion of how to make simple adjustments of F_IO_2 to improve oxygenation. It is followed by a discussion of techniques involving the use of PEEP to improve oxygenation. Achieving optimal PEEP requires close monitoring and the use of either static or dynamic pressure-volume loops. Methods used to set optimal PEEP are provided along with a review of pressure-volume loops. Additional uses of PEEP are also discussed in this chapter, along with a description of the effects, complications, and consequences associated with discontinuation of PEEP.

A discussion of the pathophysiology of acute respiratory distress syndrome (ARDS) is included to provide the reader with an understanding of the complexity of this disorder. Patients with ARDS are among the most difficult to oxygenate and manage in the critical care unit. The concept of lung-protective strategies and lung recruitment maneuvers (RMs) that are currently being used to improve oxygenation, particularly in patients with ARDS, are included, along with three clinical scenarios related to the topics discussed in this chapter.

BASICS OF OXYGENATION USING F_IO_2, PEEP STUDIES, AND PRESSURE-VOLUME CURVES FOR ESTABLISHING OPTIMAL PEEP

Basics of Oxygen Delivery to the Tissues

The most common parameters used to assess the oxygenation status of patients are the F_IO_2, S_pO_2, ABGs, hemoglobin (Hb), presence of abnormal Hb species, P_aO_2, P_aO_2/P_AO_2, P_aO_2/F_IO_2, shunt, cardiac output, mixed venous O_2 saturation (SvO_2), and O_2 content of mixed venous blood ($C\bar{v}O_2$). Measuring DO_2 to the tissues provides valuable information about O_2 availability to the tissues. O_2 utilization by the tissues can be determined by measuring arterial-to-mixed venous O_2 content difference ($C[a-\bar{v}]O_2$), O_2 consumption ($\dot{V}O_2$), cardiac output, and SvO_2. Table 13.1 provides a list of normal values for the parameters used to evaluate a patient's oxygenation status. Box 13.2 contains a summary of the equations for calculating parameters that are not directly measured, such as the partial pressure of alveolar O_2 (P_AO_2), C_aO_2, $C\bar{v}O_2$, and DO_2.

Evaluating P_aO_2, S_pO_2, and F_IO_2 in Ventilator Patients

The F_IO_2 should be measured at regular intervals or continuously, if possible, to ensure that the patient is receiving the appropriate concentration of inspired O_2. When changes in the F_IO_2 are initially made for adult patients, ABGs should be measured within 15 minutes, although some clinicians choose to obtain a sample after 30 minutes.[1,2] Many clinicians often rely on pulse oximetry

TABLE 13.1 Measures and Values Used in the Evaluation of Oxygenation Status

Term	Abbreviation	Normal Value
Partial pressure of arterial oxygen	P_aO_2	80–100 mm Hg
Partial pressure of mixed venous oxygen	PvO_2	40 mm Hg
Alveolar partial pressure of oxygen	P_AO_2	100–673 mm Hg
Fraction of inspired oxygen	F_IO_2	F_IO_2 range: 0.21–1.0
Alveolar-arterial oxygen tension gradient	$P_{(A-a)}O_2$	5–10 mm Hg (F_IO_2 = 0.21) 30–60 mm Hg (F_IO_2 = 1.0)
Ratio of P_aO_2 to fractional inspired oxygen (P_aO_2 range = 80–100 mm Hg; F_IO_2 = 0.21)	P_aO_2/F_IO_2	380–475
Ratio of P_aO_2 to partial pressure of alveolar oxygen (P_aO_2 range = 80–100 mm Hg; F_IO_2 = 0.21)	P_aO_2/P_AO_2	0.8–1.0
Saturation of arterial oxygen	S_aO_2	97%
Saturation of mixed venous oxygen	SvO_2	75%
Oxygen content of arterial blood	C_aO_2	20 vol%
Oxygen content of mixed venous blood	$C\bar{v}O_2$	15 vol%
Oxygen delivery	DO_2	1000 mL/min
Oxygen consumption	$\dot{V}O_2$	250 mL/min

BOX 13.2 Equations Used to Calculate Oxygenation Status: Alveolar Air Equation (Calculation of Alveolar PO_2, P_AO_2)

$$P_AO_2 = F_IO_2(P_B - P_{H_2O}) - \left[PaCO_2\left\{F_IO_2\left(1 - \frac{F_IO_2}{R}\right)\right\}\right]$$

where P_AO_2 = alveolar partial pressure of O_2 (mm Hg)
F_IO_2 = inspired O_2 fraction
P_B = barometric pressure (mm Hg)
PH_2O = water vapor pressure (at 37° C = 47 mm Hg)
R = respiratory quotient ($\dot{V}O_2$; R of 0.8 is commonly used)
With an $F_IO_2 \leq 0.6$ (low value), the effect of R on P_AO_2 is small.
To estimate the P_AO_2 for F_IO_2 values <0.6: $P_AO_2 = F_IO_2(P_B - PH_2O) - (1.25 \times P_aCO_2)$
Partial pressure of inspired O_2: $P_IO_2 = F_IO_2\ (P_B - PH_2O)$
Arterial O_2 content (C_aO_2): $C_aO_2 = ([Hb \times 1.34] \times S_aO_2) + (0.003\ mL/dL \times P_aO_2)$
Mixed venous O_2 content ($C\bar{v}O_2$): $C\bar{v}O_2 = ([Hb \times 1.34] \times S\bar{v}O_2) + (0.003°mL/dL \times P\bar{v}O_2)$
O_2 consumption ($\dot{V}O_2$): V
O_2 delivery (DO_2): DO_2 = C.O. × C_aO_2

measurements to assess the oxygenation of neonatal and pediatric patients, thus reducing the frequency of ABGs ordered for these patients.

Every attempt should be made to prevent complications associated with O_2 toxicity by administering an F_IO_2 below 0.6 while maintaining the P_aO_2 between 60 and 90 mm Hg and the C_aO_2 near normal (20 mL/dL). This goal is not always possible, and sometimes a higher F_IO_2 is required. (See section on selection of F_IO_2 or adjusting mean airway pressure.)

The S_pO_2 can be used to titrate F_IO_2 once the relationship between P_aO_2 and S_pO_2 has been established. (After mechanical ventilation is initiated, an arterial blood gas [ABG] sample is obtained and the P_aO_2 is compared with the patient's current S_pO_2 to establish this relationship.) A goal for maintaining S_pO_2 at greater than 90% is appropriate. It is important to understand, however, that the S_pO_2 will not always correlate perfectly with P_aO_2. Some patients will have a large discrepancy between S_pO_2 and P_aO_2 and need to be monitored more carefully[3] (see Chapter 10). For example, in patients with chronic obstructive pulmonary disease (COPD), their normal P_aO_2 may be near 55 mm Hg (S_aO_2 ~80%) and the S_pO_2 values may be closer to 88% to 90% on room air.

Although the inspired O_2 percentage can be determined using multiuse O_2 analyzers, most intensive care unit (ICU) ventilators have built-in O_2 analyzers that can provide continuous measurements of F_IO_2. Examples include the Dräger Infinity Evita V500 Critical Care Ventilator (Drägerwerk AG & Co. KGaA, Lubeck, Germany), the Hamilton-C3 and G5 ventilators (Hamilton Medical, Bonaduz, Switzerland), the Medtronics PB 980 (Medtronic Minimally Invasive Therapies, Medtronics, Minneapolis, MN), and the Servo-i, Servo-s, and Servo-U ventilators (Getinge, Wayne, NJ).

Adjusting F_IO_2

The ABGs obtained after mechanical ventilation is initiated are compared with the F_IO_2 being delivered. A linear relationship exists between P_aO_2 and F_IO_2 for any patient as long as the person's cardiopulmonary status remains fairly stable.[4–7] In other words, the minute ventilation, cardiac output, shunt, and ratio of volume of dead space to tidal volume (V_D/V_T) must not change significantly between the time the ABG comparison is made and the F_IO_2 is changed. Most of the time, this is the case because ventilator changes are made quickly after blood gas results are obtained.

Because of this linear correlation, the known P_aO_2 and the known F_IO_2 can be used to select the F_IO_2 necessary to achieve a desired P_aO_2:

$$\frac{P_aO_2(\text{Known})}{F_IO_2(\text{Known})} = \frac{P_aO_2(\text{Desired})}{F_IO_2(\text{Desired})}$$

or

$$C[a - \bar{v}]O_2$$

This equation provides a reliable method for making appropriate changes in the F_IO_2 to achieve a desired P_aO_2.

Some institutions use the ratio of P_aO_2/P_AO_2 for evaluation of oxygenation and for predicting the inspired O_2 concentration.[7–10] The ratio of P_aO_2 to F_IO_2 (commonly called the *P-to-F ratio* [P_aO_2/F_IO_2]) also has become a popular way to set F_IO_2 because of its simplicity. To estimate the change in F_IO_2, for example, if the P_aO_2 is 60 mm Hg with an F_IO_2 of 0.3 and the target P_aO_2 is 80 mm Hg, the calculation of F_IO_2 is as follows:

$$\frac{\text{Known } P_aO_2}{F_IO_2(\text{Known})} = \frac{\text{Desired } P_aO_2}{F_IO_2(\text{Desired})}$$

and 60/0.3 = 80/X, where X would be the new F_IO_2 setting. In this example, the new setting for F_IO_2 would be 0.4 (Case Study 13.2).[8,9] Making adjustments in F_IO_2 has a greater effect on patients with hypoventilation and reduced ventilation-perfusion $\dot{V}/\dot{Q}$, in which higher alveolar O_2 has better access to pulmonary blood flow than situations of pulmonary shunt. Using the *P-to-F ratio* (P_aO_2/F_IO_2) to adjust the F_IO_2 is not as accurate as using the P_aO_2/P_AO_2 because the alveolar PO_2 determination takes P_aCO_2 into account.

Selection of F_IO_2 or Adjustment of Mean Airway Pressures

Although the exact safe level of F_IO_2 in mechanically ventilated patients is not known at this time, it is generally agreed that maintaining a high F_IO_2 (>0.6) can result in O_2 toxicity.[11] Besides the tissue damage associated with long-term use of 100% O_2, it also has an additional complication. Breathing 100% O_2 can lead to **absorption atelectasis** and increase intrapulmonary shunting (i.e., shunt fraction), which further contributes to hypoxemia

Case Study 13.2

Changing F_IO_2

After being supported on a ventilator for 30 minutes, a patient's P_aO_2 is 40 mm Hg on an F_IO_2 of 0.75. Acid-base status is normal, and all other ventilator parameters are within the acceptable range. PEEP is 5 cm H_2O. What F_IO_2 is required to achieve a desired P_aO_2 of 60 mm Hg? Is your answer possible? Can you think of another form of therapy to improve oxygenation?

BOX 13.3 Pulmonary Shunt: Perfusion Without Ventilation

As the percentage of pulmonary shunt (i.e., shunt fraction or $\dot{Q}_S/\dot{Q}_T$) increases, hypoxemia worsens. A number of pathological conditions are associated with an increased shunt fraction. Examples include atelectasis, pulmonary edema, pneumonia, pneumothorax, and complete airway obstruction.

Pulmonary Shunt Calculations

$$\frac{\dot{Q}_S}{\dot{Q}_t} = \frac{(C_{c'}O_2 - C_aO_2)}{(C_{c'}O_2 - C\bar{v}O_2)}$$

where $\dot{Q}_S$ is the shunted portion, $\dot{Q}_T$ is total cardiac output, $C_c'O_2$ is the content of O_2 of the alveolar capillary (also called *pulmonary end-capillary*), C_aO_2 is the arterial O_2 content, and CvO_2 is the mixed venous O_2 content. $C_c'O_2$ is calculated based on the assumption that pulmonary end-capillary PO_2 is the same as P_AO_2.

Both arterial and mixed venous blood samples are required for this calculation. As previously mentioned, arterial blood can be obtained from a peripheral artery. Mixed venous blood is taken from the distal port of a pulmonary artery catheter (see Chapter 11).

End-capillary O_2 content ($C_c'O_2$ = ([1.34 × Hb] × 1.0) + (0.003 × P_AO_2), arterial O_2 content (C_aO_2) = ([1.34 × Hb] × S_aO_2) + (0.003 × P_aO_2) and mixed venous O_2 content ($C\bar{v}O_2$) = ([1.34 × Hb] × $C\bar{v}O_2$) + (0.003 × $C\bar{v}O_2$).

(Box 13.3).[10,12–14] Thus F_IO_2 should be kept as low as possible. Although the lower limits of permissive hypoxemia remain controversial, most practitioners agree that a target P_aO_2 of 60 mm Hg and an S_pO_2 of 90% are acceptable lower limits for most adult patients.[12] If the P_aO_2 remains very low while the patient is breathing an enriched O_2 mixture, significant shunting, $\dot{V}/\dot{Q}$ abnormalities, and/or diffusion defects are present. In these cases, other methods to improve oxygenation, besides increasing F_IO_2, must be considered. One approach that can be used to increase the P_aO_2 involves increasing the $\bar{P}_{aw}$. The $\bar{P}_{aw}$ is the average pressure above baseline during a total respiratory cycle (I + E) (Fig. 13.1).

Box 13.4 provides an equation to estimate P_{aw}. As $\bar{P}_{aw}$ increases, the P_aO_2 increases. Factors that affect $\bar{P}_{aw}$ during positive pressure ventilation include peak inspiratory pressure (PIP), total PEEP (i.e., intrinsic PEEP or auto-PEEP plus extrinsic or set PEEP [$PEEP_E$]), inspiratory-to-expiratory (I/E) ratios, respiratory rate (*f*), and inspiratory flow pattern. For example, as the total PEEP increases, the $\bar{P}_{aw}$ increases. $\bar{P}_{aw}$ is a major determinant of oxygenation in patients with ARDS because it affects mean alveolar pressure ($\bar{P}_{aw}$) and alveolar recruitment and therefore oxygenation.[15–19] Thus PEEP is typically used to increase $\bar{P}_{aw}$, although other approaches are also available. For example, high-frequency oscillatory ventilation (HFOV) and airway pressure release ventilation (APRV) can also be used to increase $\bar{P}_{aw}$. (HFOV and APRV are reviewed in Chapter 23.) At one time, inverse ratio ventilation (IRV) was used by many clinicians; however, this strategy is not routinely used today (Box 13.5).[15–24]

INTRODUCTION TO POSITIVE END-EXPIRATORY PRESSURE AND CONTINUOUS POSITIVE AIRWAY PRESSURE

Because PEEP is so frequently used to increase $\bar{P}_{aw}$ and improve and maintain oxygenation, it occupies a key role as a technique for treating acute parenchymal lung injury, such as severe atelectasis associated with various pulmonary pathological processes. The goal of using PEEP is to recruit collapsed alveoli while avoiding overdistention of already open alveoli.[25] It is important to set an appropriate level of PEEP that avoids overdistention while maintaining alveolar patency and preventing alveoli from collapsing during exhalation of a tidal volume. Both overdistention and repeated collapse and reexpansion of alveoli are associated with ventilator-induced lung injury (VILI) (see Chapter 17 for more details about the effects of PEEP and VILI). The following section reviews the pathophysiology of atelectasis, indications for using PEEP and CPAP, and techniques used to establish an appropriate level of PEEP for a patient.

Pathophysiology of Atelectasis

Atelectasis is defined as the partial or complete collapse of previously expanded areas of the lung producing a shrunken, airless state. It can result from blockage of air passages, shallow breathing (e.g., postoperative atelectasis), or surfactant deficiency. The loss of

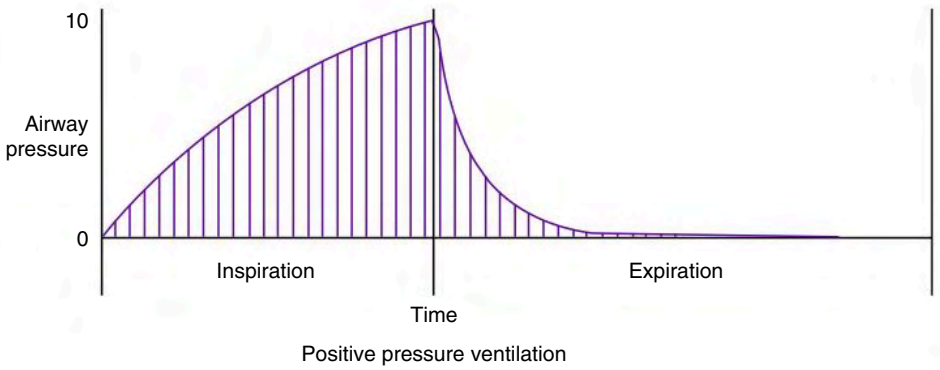

Fig. 13.1 A pressure-time waveform illustrating mean airway pressure (P_{aw}). Vertical lines under the pressure-time curve represent frequent readings of pressure over the total respiratory cycle. The sum of these pressure readings (i.e., the area under the curve) divided by the cycle time will give the value for mean airway pressure. (See text for additional information.)

BOX 13.4 Simple Method for Calculating

$$P_{aw} = \frac{1}{2}\left[PIP \times \left(\frac{\text{inspiratory time}}{\text{total respiratory cycle}}\right)\right]$$

When PEEP is used, the equation is as follows:

$$\bar{P}_{aw} = \frac{1}{2}(PIP - PEEP) \times \left(\frac{\text{inspiratory time}}{\text{total cycle time}}\right) + PEEP$$

Fortunately, most ICU ventilators measure pressures and time and perform this calculation automatically.

BOX 13.5 Inverse Ratio Ventilation (IRV)

IRV is one method for increasing $\bar{P}_{aw}$, in which inspiratory time (T_I) is longer than expiratory time (T_E). IRV can be used with either pressure-controlled or volume-controlled ventilation. The rationale behind increasing T_I is to recruit lung units and avoid overinflating normal units. Keeping alveoli open for extended periods may reduce shunt and $\dot{V}/\dot{Q}$ mismatch.

When an inverse I/E ratio is used with pressure ventilation (PC-IRV), a longer T_I will increase $\bar{P}_{aw}$. With PC-IRV, the PIP and PEEP do not change because these are set values. However, volume delivery varies with changes in compliance and resistance. Exhaled V_T and $\dot{V}_E$ must be closely monitored. (NOTE: Increase in auto-PEEP reduces V_T delivery in PC-IRV.) In addition, using IRV may require sedation and paralysis in a number of patients because an increased I/E breathing pattern is uncomfortable.

Volume control inverse ratio ventilation (VC-IRV) is an alternative to PC-IRV, but it is seldom used. With VC-IRV, V_T is ensured, if this is a desired goal. VC-IRV can be accomplished by selecting VC-CMV, using a descending waveform to lengthen T_I or setting a longer T_I if the ventilator is time cycled. T_I can be further lengthened by adding inspiratory pause and slowing inspiratory flows.

It is important to recognize that IRV can create several risks for patients. Both dynamic hyperinflation (auto-PEEP) and increased $\bar{P}_{aw}$ can increase the risk for lung damage. Furthermore, cardiac output may decrease with increased $\bar{P}_{aw}$. An I/E ratio of 2:1 is therefore rarely exceeded because of adverse hemodynamic consequences.

Manipulating pressures to increase $\bar{P}_{aw}$ may result in injury to the lung from trapped air and overdistention and possibly barotrauma (e.g., pneumothorax). (See Chapter 17 for pulmonary complications of positive pressure ventilation.) High thoracic pressures can reduce venous return and cardiac output.[3] (See Chapter 16 for cardiovascular complications.) Therefore it is important to monitor the $\bar{P}_{aw}$ and assess the patient's response.

surfactant can be a result of damage to surfactant-producing cells (type II pneumocytes), leakage of plasma proteins that inhibit surfactant production, or the presence of inflammatory mediators (e.g., **cytokines**). These factors tend to promote atelectasis, particularly in the presence of high O_2 concentrations, pulmonary edema, general anesthesia, mechanical ventilation, chemical toxicity, and ARDS.

The treatment of acute atelectasis involves identifying the cause and then initiating an appropriate corrective action. For mechanical obstruction of the airways, coughing, suctioning, percussion, and therapeutic fiberoptic bronchoscopy may be indicated to clear the obstruction. Therapy with PEEP or CPAP may also be used to help inflate (i.e., recruit) collapsed alveoli.

Goals of PEEP and CPAP

The goals of PEEP/CPAP therapy are:

1. Maintain a P_aO_2 60 mm Hg or greater and S_pO_2 at 90% or greater, at an acceptable pH
2. Recruit alveoli and maintain them in an aerated state
3. Restore functional residual capacity
4. Enhance tissue oxygenation

Achieving these goals may provide opportunities to reduce the F_IO_2 to safer levels (<0.6). Note that sustaining cardiovascular function and avoiding lung injury are critical requirements for effective PEEP/CPAP therapy.

Terminology

The term *PEEP* as it is commonly used implies that the patient is receiving mechanical ventilatory support and the baseline (i.e., end-expiratory) pressure is above zero cm H_2O. CPAP is pressure above the ambient pressure maintained during spontaneous ventilation. With CPAP, expiratory positive airway pressure and inspiratory positive airway pressure are both positive and equal, albeit the ventilator does *not* provide mandatory breaths.

Technical Aspects of PEEP and CPAP Devices

Generally, PEEP is used when a problem in the lungs results in collapse of alveoli and small airways (atelectasis). If a significant number of alveoli collapse, more areas of the lung are perfused but not ventilated, resulting in a shuntlike situation.

When PEEP is set on a ventilator, the expiratory valve of the ventilator closes when the expiratory pressure drops to the set PEEP level. This traps a certain amount of pressure and volume in the lungs that can prevent or reverse alveolar collapse and reduce the amount of pulmonary shunting.

Although CPAP can be used to reduce shunting, as mentioned earlier, its application is for patients who are spontaneously breathing. CPAP can be achieved with a mechanical ventilator by setting the mode selection switch to the spontaneous/CPAP mode and then setting the desired level of CPAP (PEEP control). CPAP can be delivered to spontaneously breathing patients using a freestanding setup (i.e., one without a mechanical ventilator). It is important to recognize that using freestanding CPAP devices carries a potential liability because these devices are usually "homemade" and have not undergone a formal evaluation for approval by an authorized independent agency. (Freestanding CPAP systems are discussed in more detail later in this chapter.)

Application of CPAP and PEEP to the Patient's Airway

The positive pressure employed with CPAP or PEEP is commonly applied to the airway noninvasively with a mask or nasal prongs or invasively through an endotracheal tube (ET) or a tracheostomy tube. Noninvasive CPAP administered with a soft silicon mask eliminates the need for endotracheal intubation in specified groups

of patients (see Chapter 19). A variety of tight-fitting masks can be applied to the face or nose, with the pressure adjusted to as high as 15 cm H_2O (see Figs. 19.4, 19.6, and 19.7). Excessive leakage around the mask, however, can create a problem when trying to maintain a desired pressure.

Mask CPAP

Patients receiving mask CPAP are usually alert, awake, and oriented. These patients can protect their lower airways, support work of breathing (WOB), and maintain a normal P_aCO_2 without excessive ventilatory effort. Patients receiving noninvasive mask CPAP should have a P_aO_2/F_IO_2 ratio greater than 200 mm Hg and stable cardiovascular status. The hazards and complications of mask CPAP can include vomiting and aspiration, skin necrosis or discomfort from the mask, CO_2 retention, increased WOB, and cerebral hemorrhage at high CPAP levels (infants).

Nasal CPAP

By taking advantage of the fact that neonates are obligate nose breathers, plastic or Silastic nasal prongs can be fitted into an infant's nares. CPAP pressures up to about 15 cm H_2O can be administered with these devices (see Fig. 22.2). Loss of pressure from the system can occur through the mouth at high pressures (>15 cm H_2O) (Case Study 13.3). Problems of nasal CPAP include gastric distention, pressure necrosis, swelling of nasal mucosa, and abrasion of the posterior pharynx. (See Chapter 22 for additional information on nasal CPAP in infants.)

Endotracheal or Tracheostomy Tubes

Endotracheal intubation or placement of a tracheostomy tube may be necessary to provide an airway for the administration of CPAP for patients who do not meet the criteria for mask or nasal CPAP.

Flow and Threshold Resistors

When PEEP/CPAP is used, the flow or pressure the patient must generate to obtain inspiratory flow for a spontaneous breath or to trigger a mandatory breath depends on the type of system used. High-gas flow systems, pressurized reservoirs, demand valves, and demand flow systems respond to patient flow demand. The more rapidly and easily these devices respond to patient effort, the less WOB is required. Expiratory pressure, on the other hand, is maintained above ambient pressure with PEEP/CPAP and can be accomplished using a variety of devices that are classified as either flow or threshold resistors.

A *flow resistor* achieves expiratory pressure by creating a resistance to gas flow through an orifice. As the diameter of the orifice decreases in size, the pressure level applied increases; conversely, as the diameter of the orifice increases, the applied pressure level decreases. Changes in expiratory gas flow also affect the expiratory pressure applied with a flow resistor; that is, the pressure is flow dependent. The higher the expired gas flow, the higher is the expiratory pressure generated; the lower the expired gas flow, the lower is the pressure. (Positive expiratory pressure [PEP] mask therapy is based on this principle.) An ideal flow resistor is one in which pressure increases linearly with flow.

With *threshold resistors,* a constant pressure is provided throughout expiration regardless of the rate of gas flow (i.e., flow independent). When a threshold resistor is used in the expiratory limb of a ventilator circuit, the exhaled air passes unimpeded until pressure falls to the preset PEEP value. At that time, the expiratory gas flow stops and the system pressure is maintained at the preset PEEP level. The expiratory valves on most ventilators behave as threshold resistors. Note that these threshold resistors are free-floating and provide minimal resistance to exhalation (Key Point 13.2).

Circuitry for Spontaneous CPAP With Freestanding Systems and Mechanical Ventilators

Ventilators can provide CPAP for a spontaneously breathing patient by simply eliminating the mandatory breaths (CPAP/spontaneous mode) and adjusting the PEEP level to the desired pressure. Current ICU ventilators can be used for CPAP because they incorporate inspiratory flow systems that typically respond quickly to a patient's breathing effort and do not increase WOB.

CPAP can also be provided by a freestanding system without using a ventilator. There are two types of freestanding or stand-alone CPAP or expiratory positive airway pressure systems: continuous flow CPAP, which is a closed system; and demand-flow spontaneous CPAP, which is an open system. Both systems can be used only for patients who do not require mechanical ventilation but who might benefit from the effects of CPAP on oxygenation. Patients must be able to comfortably maintain a near-normal P_aCO_2. As mentioned previously, these systems are not used often in the clinical setting. Most institutions simply use a ventilator in the spontaneous/CPAP mode.

PEEP RANGES

Two levels or ranges of PEEP can be employed: minimum or low PEEP, also called *physiological PEEP,* and therapeutic PEEP.

Minimum or Low PEEP

In most situations it is appropriate to use a minimum level of PEEP (3–5 cm H_2O) to help preserve a patient's normal functional residual capacity (FRC). FRC usually decreases when a patient is intubated or placed in a supine position.[22–24] The reduction in FRC is primarily due to the abdominal contents moving upward and exerting pressure on the diaphragm. Because minimum PEEP involves the application of only 3 to 5 cm H_2O, it is usually not considered a problem in terms of causing complications.

Case Study 13.3

Problem Solving: Infant CPAP

An infant has been well oxygenated (S_pO_2 = 97%) using nasal CPAP at +6 cm H_2O with an F_IO_2 of 0.4. A nurse readjusts a vascular line and the infant starts crying. Pressures on the manometer drop to 0 to 2 cm H_2O, and S_pO_2 drops to 93%. What could cause the drop in S_pO_2?

***Key Point* 13.2** Adding any device to the expiratory side of a ventilator circuit that is smaller in diameter than the main expiratory line of the circuit itself will increase expiratory resistance.