of gas in the lungs, reduce dead space, and increase oxygenation by increasing mean and plateau airway pressures.
- PSV is used to support spontaneous breaths in a patient with an artificial airway when the IMV or spontaneous/CPAP modes are used.
- PRVC provides closed-loop pressure breaths and targets the pressure to achieve the set volume.
- In volume support, the set V_T is the minimum V_T. A patient can obtain a higher V_T if desired.

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

1. A respiratory therapist is determining the tubing compliance of a ventilator before use. A volume of 100 mL delivers a pressure of 33 cm H_2O. What is the compliance of the circuit?
2. After initiation of ventilation using the circuit described in Question 1, the PIP is 15 cm H_2O and the V_T set is 250 mL. What is the approximate volume actually reaching the patient?
3. A patient receiving ventilation with a CareFusion AVEA has a set V_T of 700 mL, and f is at 12 breaths/min on the VC-CMV mode. The patient is initiating another 3 breaths/min so that the total f is 15 breaths/min. What is the patient's actual $\dot{V}_E$? Also answer the following questions.
   A. If the flow is set at 30 L/min using a constant flow pattern, what is the flow in L/s?
   B. What is the TCT based on the set machine f of 12 breaths/min?
   C. What is the TCT based on the actual machine f of 15 breaths/min?
   D. What is the T_I based on the set f, flow, and V_T?
   E. What is the T_E when the f is 12?
   F. What is the T_E when the f is 15?
4. A therapist wants to select a flow waveform and flow setting for a patient with severe asthma. Which of the following is a good initial setting?
   A. Constant flow, 60 L/min
   B. Ascending flow, 80 L/min
   C. Descending flow, 70 L/min
   D. Sine flow, 40 L/min
5. A practitioner sets an inspiratory pause of 0.5 seconds to obtain a P_{plat} reading and calculate the patient's static compliance. During the measurement, a stable plateau is not seen on the pressure-time graph. What could be the problem?
6. A post–coronary artery bypass graph (CABG) surgery patient is still intubated and under the effects of anesthesia. He is being transferred from the operating suite to the recovery unit. The surgeon wants to keep ventilation pressures to a minimum and is less concerned about ventilation. The patient's body temperature is 35° C. He is 5-ft, 9-in tall and weighs 210 lb.
   A. What is the patient's BSA?
   B. What is his IBW?
   C. What is an appropriate initial $\dot{V}_E$?
   D. Would you use PC-CMV or VC-CMV and why?
   E. What V_T would be an appropriate target?
   F. Based on the V_T you selected, what would be an appropriate rate?
   G. What PEEP would you set?
7. A patient with ARDS is to be changed from a CPAP of +10 cm H_2O to VC-CMV. She is 5-ft, 4-in tall and weighs 195 lb. What tidal volume and rate would you set and why? Would pressure control ventilation be appropriate for this patient?
8. NIV is being initiated on a 54-year-old man with a history of COPD. He has an IBW of 70 kg. The initial settings are IPAP = 8 cm H_2O and PEEP = 3 cm H_2O. The patient's V_T on these settings is 280 mL and f is 27 breaths/min. What change would you recommend?
9. A patient with right lower lobe pneumonia and a temperature of 100° F needs mechanical ventilation. How should the initial $\dot{V}_E$ be adjusted? (HINT: See Box 6.1.)
10. A physician requested that her patient be switched from PC-CMV to VC-CMV to guarantee volume delivery. Ventilator parameters are VC-CMV + PSV; V_T = 0.6; f = 20 breaths/min, flow = 60 L/min (using constant flow waveform); PSV = 27 cm H_2O; PEEP = +8 cm H_2O; PIP = 56 cm H_2O; and P_{plat} = 43 cm H_2O. The physician asked the respiratory therapist to find a way to reduce pressures without changing $\dot{V}_E$. What is a possible solution?
11. A ventilator is set with PRVC with a PEEP = +5 cm H_2O, a set V_T of 650 mL, and an upper pressure limit of 30 cm H_2O. Initially the pressure required to deliver the V_T was 20 cm H_2O. After 24 hours, the pressure required to deliver the set V_T increases to 24 cm H_2O. What changes have probably occurred in the patient's lung characteristics?
12. What ventilator mode is patient triggered, pressure targeted, and flow cycled and also targets a set tidal volume?
13. The pressure-time and flow-time curves above are viewed during PC-CMV ventilation with an apneic patient. What is the P_{plat}?
14. The pressure-time curve above is observed during PSV. Which of the following would you suspect on the basis of the ventilator graphic recording?
   A. Active exhalation
   B. No sloping in the presence of increased airway resistance
   C. A leak in the circuit
   D. Active inhalation

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CHAPTER 7

Final Considerations in Ventilator Setup

OUTLINE

KEY TERMS

- Acute severe asthma
- Barotrauma
- Cushing response
- Humidity deficit
- Isothermic saturation boundary
- Pulsus paradoxus
- Relative humidity

LEARNING OBJECTIVES

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

1. Recommend fractional inspired oxygen concentration (F_IO_2) settings when initiating mechanical ventilation.
2. Discuss the pros and cons of using the sigh function during mechanical ventilation.
3. Compare the use of sigh with the concept of a recruitment maneuver in acute respiratory distress syndrome.
4. List the actions necessary for final ventilator setup.
5. Explain the concept of using extrinsic positive end-expiratory pressure in patients with airflow obstruction and air trapping who have trouble triggering a breath during mechanical ventilation.
6. Calculate the desired F_IO_2 setting given the current partial pressure of arterial oxygen (P_aO_2) and F_IO_2 values.
7. List the essential capabilities of an adult intensive care unit ventilator.
8. Provide initial ventilator settings from the guidelines for patient management for any of the following patient conditions: chronic obstructive pulmonary disease, acute asthma exacerbation, neuromuscular disorders, closed head injuries, acute respiratory distress syndrome, and acute cardiogenic pulmonary edema.

Several issues must be considered after decisions about the type of ventilator to be used, mode selection, and settings for pressure and volume have been made. These issues include selecting appropriate ventilator settings for the *fractional concentration of inspired oxygen* (F_IO_2), sensitivity, sigh breaths, alarms, and monitors, in addition to concerns regarding humidification of inspired gases. Only after these issues have been addressed can mechanical ventilation be initiated.

This chapter provides a summary of these issues and also addresses the initial settings for patients with specific pathological conditions, such as chronic obstructive pulmonary disease (COPD), asthma, neuromuscular diseases, and acute respiratory distress syndrome (ARDS).

SELECTION OF ADDITIONAL PARAMETERS AND FINAL VENTILATOR SETUP

Selection of Fractional Concentration of Inspired Oxygen

The goal of selecting a specific F_IO_2 for a patient is to achieve a clinically acceptable arterial O_2 tension (e.g., 60–100 mm Hg). To accomplish this goal, a baseline arterial blood gas (ABG) should be

performed. If the patient's partial pressure of arterial O_2 (P_aO_2) is within the desired range before beginning ventilatory support, the F_IO_2 that the patient is receiving at the time of the baseline ABG can be used when mechanical ventilation is initiated. If the P_aO_2 is not within the desired range, the following equation can be used to estimate F_IO_2:

$$\text{Desired } F_IO_2 = \frac{[P_aO_2(\text{desired}) \times F_IO_2(\text{known})]}{P_aO_2(\text{known})}$$

This relationship is based on the assumption that the patient's cardiopulmonary function will not radically change from the time of the baseline ABG to the time when mechanical ventilation is initiated.[1,2] Some changes will obviously occur because the application of positive pressure ventilation can affect a patient's cardiopulmonary status.

If a baseline ABG is not available, it is advisable to select a high initial F_IO_2 setting ($\geq$0.50) for patients with presumed severe hypoxemia. This can provide a way of restoring normal oxygenation and replacing tissue O_2 storage when O_2 debt and lactic acid accumulation have occurred. Clinicians often start with an F_IO_2 of 1.0 and then reduce it as quickly as possible. Extended use of 100% O_2 is not recommended because it can quickly result in absorption atelectasis and, in the long term, can lead to O_2 toxicity. It is important to state, however, that 100% O_2 should not be withheld if the patient is seriously ill and requires a high F_IO_2. Indeed, any procedure that places the patient at risk for developing hypoxemia should be performed with the patient breathing 100% O_2. For example, administering 100% O_2 before and after suctioning and also during bronchoscopy is a common practice.

Titrating the F_IO_2 using pulse oximetry and ABG findings can minimize the risk for administering too much O_2.[3-5] The F_IO_2 can be adjusted after ventilation is started, based initially on the pulse oximetry saturation (S_pO_2).[6] An S_pO_2 greater than 92% (P_aO_2 $\geq$60 mm Hg) is a common and acceptable goal. Within 10 to 20 minutes of beginning ventilation, an ABG sample should be collected to assess the adequacy of ventilation and oxygenation. Appropriate ventilator changes based on ABG results are reviewed in Chapters 12 and 13.

The equation for obtaining a desired F_IO_2 previously shown in this section can also be used to adjust the F_IO_2. In cases in which an F_IO_2 greater than 0.50 is required to maintain oxygenation, positive end-expiratory pressure (PEEP) may be indicated (see Chapter 13). It is important to emphasize that an F_IO_2 of 0.50 or greater increases the risk for O_2 toxicity and intrapulmonary shunting that occurs with O_2 induced atelectasis.

SENSITIVITY SETTING

Ventilator sensitivity is normally set at a level that the patient can easily flow-trigger or pressure-trigger a breath (see Chapter 3). Flow triggering is set in a range of 1 to 10 L/min below the base flow, depending on the selected ventilator. Pressure sensitivity is commonly set between −1 and −2 cm H_2O.

Many clinicians prefer using flow triggering because it provides a slightly faster response time compared with pressure triggering, for two main reasons. First, the exhalation valve does not have to close during flow triggering. With pressure triggering, the exhalation valve must close and the patient's inspiratory effort has to be sufficient to reduce the circuit pressure to the trigger setting. Second, during pressure triggering, the circuit pressure must drop before the inspiratory valve opens and flow goes to the patient.[7] In contrast, with flow triggering, the pressure does not need to drop because the inspiratory valve remains open and the patient receives almost immediate support (Key Point 7.1).

Key Point 7.1 Flow triggering has a slightly faster response time compared with pressure triggering.

BOX 7.1 Definitions of Positive End-Expiratory Pressure (PEEP)

PEEP: Positive end-expiratory pressure; airway pressure greater than zero at the end of exhalation

Extrinsic PEEP ($PEEP_E$): The level of PEEP set by the operator on the ventilator

Auto-PEEP (intrinsic PEEP, or $PEEP_I$): The amount of pressure in the lungs at the end of exhalation when expiration is incomplete (i.e., expiratory flow is still occurring) and no $PEEP_E$ is present ($PEEP_E$ is excluded from this value)

Intrinsic PEEP can occur in three situations: (1) Strong active expiration, often with normal or even with low lung volumes (e.g., Valsalva maneuver); (2) high minute ventilation (>20 L/min), where expiratory time (T_E) is too short to allow exhalation to functional residual capacity; or (3) expiratory flow limitation as a result of increased airway resistance, as may occur in patients with chronic obstructive pulmonary disease on mechanical ventilation or with small endotracheal tubes or obstructed (clogged) expiratory filters.

Total PEEP = $PEEP_E$ + auto-PEEP

If auto-PEEP (intrinsic PEEP [$PEEP_I$]) is present, patients often have difficulty triggering a breath. Indeed, in cases in which auto-PEEP is high, patients may be unable to trigger a breath. A relatively simple method of assessing if auto-PEEP if present is to palpate the accessory muscles of inspiration (e.g., sternocleidomastoid muscles). Therefore it can be particularly difficult when a high level of auto-PEEP is present to adjust the ventilator sensitivity so that it senses patient effort. Furthermore, the cause of the problem often goes unsolved unless auto-PEEP is detected and measured (Box 7.1).

When auto-PEEP occurs in mechanically ventilated, spontaneously breathing patients with airflow obstruction (e.g., in COPD), setting the extrinsic PEEP ($PEEP_E$) level to equal about 80% of the patient's auto-PEEP level may improve the ventilator's response (i.e., sensitivity) to the patient's inspiratory efforts. Fig. 7.1A and B helps illustrate this problem. Imagine that you are trying to sip water through a straw from a glass in which the water level is 10 cm below your mouth. You would have to generate at least −10 cm H_2O to draw the water into your mouth. A similar situation occurs in patients on ventilation with air trapping who are trying to trigger a breath. The patient must create a pressure gradient between the alveolus and mouth by decreasing alveolar pressure (P_{alv}) to zero or lower so that mouth pressure (P_M) is greater than P_{alv}. This gradient allows air to flow into the lungs. For example, if +10 cm H_2O of auto-PEEP was present, the patient would have to generate an effort equal to −10 cm H_2O to achieve a P_{alv} of zero. Then the patient must generate an additional −1 to −2 cm H_2O to trigger inspiratory flow.

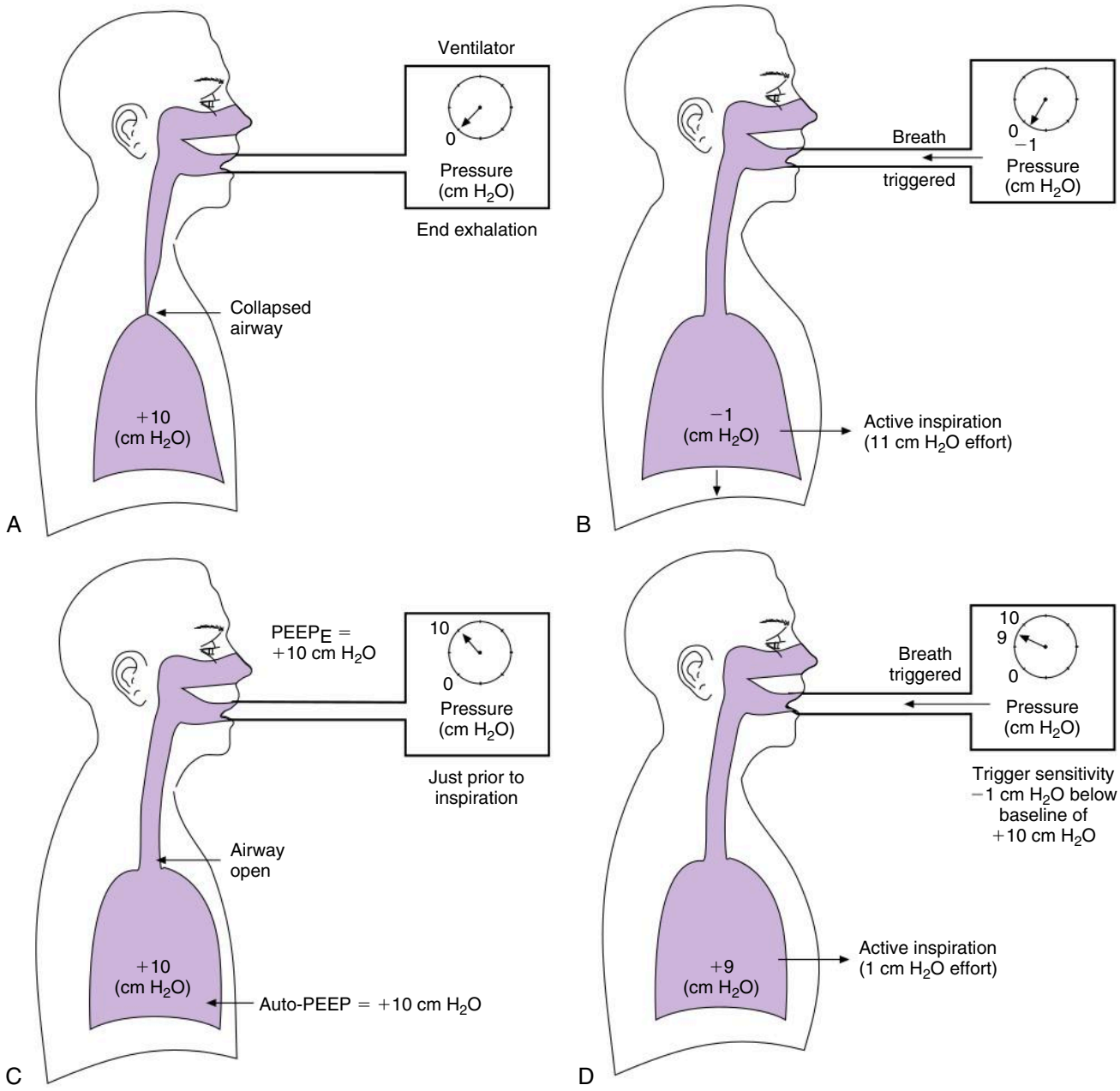

Fig. 7.1 Representation of a patient with air trapping (auto-PEEP) and airway collapse trying to trigger a ventilator breath. (A) 10 cm H_2O of auto-PEEP at end exhalation. (B) The patient's alveolar pressure (P_{alv}) must drop to −1 cm H_2O to trigger a ventilator breath. The effort required is the sum of the auto-PEEP level plus the trigger sensitivity setting of the ventilator, +10 cm H_2O (auto-PEEP) plus 1 cm H_2O (sensitivity), equals 11 cm H_2O of effort. (C) Extrinsic PEEP ($PEEP_E$) set to +10 cm H_2O helps open airways and, for this example, did not increase peak inspiratory pressure. (D) Triggering is accomplished with only −1 cm H_2O of effort.

Another approach to solving the straw-sipping problem is to fill the glass with more water, which in turn would bring the water level closer to the mouth. Similarly, the problem that patients with auto-PEEP have with triggering a breath can be solved by increasing pressure at the mouth (PEEP) until it equals P_{alv} (i.e., the pressure gradient between the mouth and the alveolus is reduced). This reduction is accomplished by applying PEEP with the ventilator (see Fig. 7.1C). PEEP can be added until most of the airways are no longer collapsed, and the patient only has to generate enough pressure to trigger the ventilator based on the sensitivity setting. Note that this technique will not be effective if the auto-PEEP is the result of a high minute ventilation ($\dot{V}_E$) and if there is insufficient expiratory time (T_E).[4]

There are several relatively easy ways to estimate the amount of $PEEP_E$ to add, if auto-PEEP cannot be measured. The clinician can increase $PEEP_E$ until peak inspiratory pressure (PIP) begins to increase. This increase in PIP is an indication that more pressure and volume have been added to the lung. Another technique of estimating the amount of $PEEP_E$ to add is to observe whether activity of the accessory muscles of breathing (e.g., sternocleidomastoids) decreases as $PEEP_E$ is added (Case Study 7.1). Still another technique involves comparing the number of triggered

Case Study 7.1

Auto-PEEP and Triggering

A 60-year-old man with COPD is receiving pressure-supported ventilation (PSV). He appears to be having difficulty triggering ventilator breaths. Auto-PEEP is measured at +8 cm H_2O, and no $PEEP_E$ is being used. Sensitivity is set at −1 cm H_2O. How much of an effort (in cm H_2O) must the patient generate to trigger a breath?

breaths with the number of patient efforts. As the level of set PEEP is increased, the number of triggered breaths should match the patient's efforts. Chapters 13 and 17 provide additional information about the complications associated with auto-PEEP, its causes, and methods to reduce auto-PEEP.

It is important to mention that the type of humidifier system being used can also influence the sensitivity. If the humidifier is located between the patient and the point at which the ventilator detects triggering, the patient has to work harder to trigger a breath. When the trigger device is located proximal to the patient's airway, this is less of a problem.[3]

Humidification

A spontaneously breathing individual's inspired air is typically conditioned down to the fourth or fifth generation of subsegmental bronchi (i.e., the **isothermic saturation boundary**) (Fig. 7.2).[8] Under normal circumstances, conditioning of inspired air occurs as air passes through the nose and upper airway. Because these are bypassed during invasive ventilation, a humidity source must be added to the ventilator circuit.

The humidification system used during mechanical ventilation should provide at least 30 mg H_2O/L of absolute humidity at a temperature range of about 33° to 37° C for all available flows up to a $\dot{V}_E$ of 20 to 30 L/min.[9,10] Some clinicians prefer a delivered temperature range of 35° to 37° C.[5]

Heated Humidifiers

Humidity can be provided by a variety of heated humidification systems. Devices in this category include the following types of humidifiers: pass-over, vapor phase, wick, and active heat and moisture exchanger.[10-12] Refilling heated humidifiers is best accomplished by using a closed-feed system. With a closed-feed system, the water level in the reservoir is maintained manually by adding water from a bag through a fill port or by a float-feed system that maintains a relatively constant water level. (Notice that another advantage of the closed-feed system is that the water temperature can be better regulated.) Both types avoid the need to open the ventilator circuit to refill the device and thus reduce the risk for potential contamination.

Heated humidifiers typically include a servo-controlled heater with a temperature probe that is placed close to the patient's airway. These devices are typically equipped with a temperature display and temperature alarm. The high-temperature alarm is set at 37° C. A minimum alarm setting of 30° C is appropriate.[8,9,13]

Whenever the temperature in the patient circuit is less than the temperature of the gas leaving the humidifier, condensate accumulates in the circuit. Notice that condensate accumulation (rain-out) increases as the room temperature becomes cooler.[14,15]

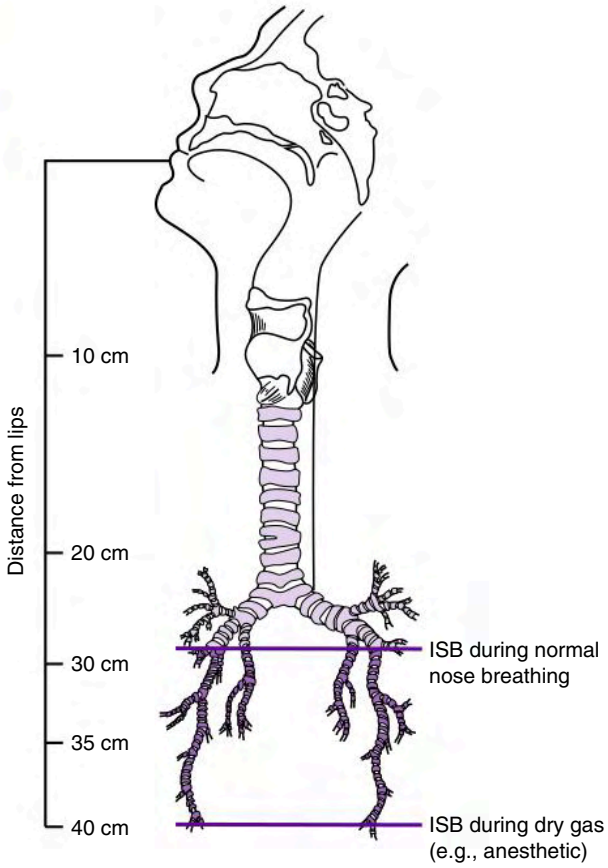

Fig. 7.2 Position of the isothermic saturation boundary (ISB) during normal nose breathing and during inhalation of dry gases (during intubation). (Redrawn from Branson RD, Campbell RS, Johannigman JA, et al.: Comparison of conventional heated humidification with a new active hygroscopic heat and moisture exchanger in mechanically ventilated patients, *Respir Care* 44:912–917, 1999.)

CRITICAL CARE CONCEPT 7.1

Changes in Relative Humidity

Gas leaves a heated humidifier at a temperature of 34° C and 100% relative humidity. The absolute humidity is 37 mg/L. The gas enters a heated wire circuit that is heated to 37° C at the proximal airway. What is the absolute humidity of the gas that is 100% saturated at normal body temperature? What is the humidity deficit (i.e., the difference between what is provided by the humidifier and the amount of humidity required by the patient)? What happens to the relative humidity of the gas as it leaves the humidifier and enters the circuit?

(Using heated wire circuits on the inspiratory and expiratory lines of the circuit can significantly reduce the amount of rain-out.)

It is important to understand that if the temperature of the gas in the patient circuit is higher than in the humidifier, the **relative humidity** in the circuit decreases (Critical Care Concept 7.1).[8] (This can occur when using heated wire circuits.) Drying of secretions can occur if a deficit exists between the amount of

humidity provided and the amount needed by the patient. Assessing whether a **humidity deficit** is present can be easily determined by examining the patient's secretions. For example, thick secretions that are difficult to suction or the presence of bronchial casts and mucous plugs are signs of drying of the airways.

Without a heated wire circuit, the humidifier may need to be heated to as much as 50° C for the gas temperature to come near to body temperature (37° C) by the time it reaches the patient's upper airway. As the highly saturated and warm gas passes through the ventilator circuit, ambient air surrounding the circuit tubing cools this gas and condensate forms in the circuit. Placing water traps at gravity-dependent parts of the circuit to capture excessive rain-out can help alleviate this problem. Water traps should be emptied regularly in a manner that protects the practitioner from any aerosolized spray that may be produced when the trap is opened. Some water traps have spring-loaded caps that seal the circuit when they are unscrewed. Others have suction ports from which excess water can be suctioned. Water traps that remain sealed during emptying help avoid interruption in ventilation during the process (Key Point 7.2). Maintaining a seal prevents breaking the circuit and thus reduces the risk for introducing contaminants.

Key Point 7.2 Condensate in the circuit tubing can potentially be a source of accidental lavage when the patient is turned. This water should be directed away from the patient and never allowed to enter the patient's airway.

Heat-Moisture Exchangers

Heat-moisture exchangers (HMEs), or artificial noses, can also be used for humidification in patients receiving mechanical ventilation. However, there are some circumstances in which HMEs should *not* be used (Box 7.2).[9,13,16] HMEs can provide 10 to 14 mg/L of water at tidal volumes (V_Ts) of 500 to 1000 mL. More efficient hygroscopic heat and moisture exchangers (HHMEs) can provide 22 to 34 mg/L at similar volumes.[8] Because a net heat and water loss occurs when HMEs are used for extended periods, the patient should be assessed for signs of drying secretions.

Most HMEs have a resistance to flow between 2.5 and 3.5 cm H_2O/L/min.[8] During extended use, HMEs can accumulate moisture and secretions, resulting in an increased resistance to flow. This increased resistance can cause gas trapping (i.e., auto-PEEP) and increase expiratory work of breathing (WOB). If more than four HMEs are used during a 24-hour period because of secretion buildup, it is probably advisable to change to a heated humidifier that provides 100% relative humidity at 31° to 35° C.[17]

It is also important to recognize that HMEs add mechanical dead space (V_{Dmech}) to the ventilator circuit. The dead space for most HMEs ranges from about 50 to 100 mL. This is an important consideration when HMEs are used on patients with low V_T, such as infants, children, and adult patients with V_T of 400 mL or less (Key Point 7.3).

Key Point 7.3 Passive humidifiers (heat-moisture exchangers) placed at the endotracheal tube should not be used simultaneously with heated humidifiers. Water produced by the heated humidifier can occlude the filter and significantly reduce airflow to the patient.[8]

HMEs should be taken out of line during delivery of an aerosolized medication. It should be kept in mind, however, that circuit disconnection increases the risk for circuit contamination. An alternative approach is to use a metered-dose inhaler (MDI) with an MDI adapter placed between the HME and endotracheal tube (ET). If a spacer is used with the MDI on the inspiratory line, the HME must still be removed. Another solution is to use a circuit adapter that does not require the HME to be removed during aerosol treatments (Fig. 7.3).

Although some manufacturers recommend changing HMEs every 24 hours, replacement may be required only every 2 to 3 days if the HME is not partially obstructed with secretions.[3,8,18] Clinicians have reported using HMEs for up to 5 days without difficulties.[19] However, if secretions appear thick after two consecutive suctioning procedures, the HME should be removed and the patient switched to a heated humidification system.[8] For critically ill patients requiring more than 5 days of ventilation, it is probably better to use a heated humidification system that will optimize humidification and help prevent secretion retention. Long-term use (longer than 7 days) of HMEs for the critically ill patient can increase the rate of ET occlusion. On the other hand, patients in long-term care facilities with tracheostomy tubes in place can use artificial noses for more extended periods without difficulty, as long as secretions do not present a problem.[19]

BOX 7.2 Contraindications for Heat-Moisture Exchangers

1. The presence of thick, copious, or bloody secretions. These secretions can accumulate on the heat-moisture exchanger (HME) and increase both inspiratory and expiratory resistance.
2. The patient's exhaled tidal volume (V_T) is less than 70% of inhaled V_T (e.g., in bronchopleural fistulas or when endotracheal tube cuffs are absent).
3. Body temperatures below 32° C (hypothermia).
4. Spontaneous high minute ventilation ($\dot{V}_E$) is greater than 10 L/min.
5. An aerosolized medication must be given.
6. Very small V_T must be delivered (lung protective ventilation), in which case the HME may significantly increase mechanical dead space (V_{Dmech}) and compromise CO_2 clearance. Notice that large V_T delivery may compromise the ability of the HME to humidify inspired gases.

ALARMS

Audible and visible alarm systems are designed to alert the clinician of potential dangers related to the patient-ventilator interaction. This section reviews the most commonly used ventilator alarms and how they are set by most clinicians.[20,21] Box 7.3 shows the various levels of alarms and gives some examples of what causes them to become activated.

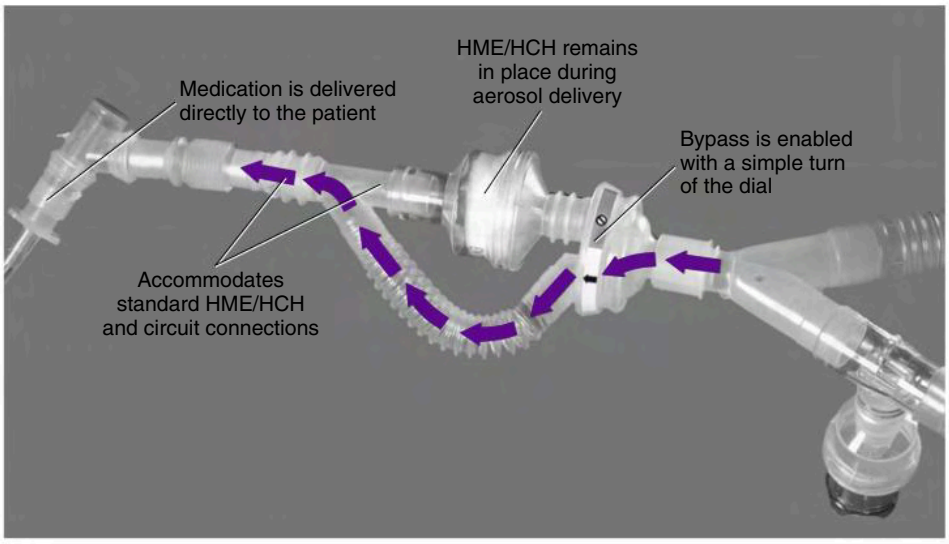

Fig. 7.3 The CircuVent ventilator circuit adapter. Aerosol delivery can be accomplished with a heat-moisture exchanger (HME) in line without breaking (disconnecting) the circuit. The practitioner turns the dial to redirect flow during medication delivery. Hygroscopic condenser humidifier (HCH). (From DHD Healthcare, Wampsville, N.Y.)

BOX 7.3 Levels of Alarm and Example Events During Mechanical Ventilation

Level 1: Immediately Life-Threatening

Example events:

- Electrical power failure
- No gas delivery to patient
- Exhalation valve failure
- Excessive gas delivery to patient
- Timing failure

Level 2: Potentially Life-Threatening

Example events:

- Circuit leak
- Circuit partially obstructed
- Heater/humidifier malfunction
- Inspiratory-to-expiratory (I/E) ratio inappropriate
- Inappropriate O_2 level (gas/blender failure)
- Autocycling
- Inappropriate PEEP/CPAP level (too low/too high)

Level 3: Not Life-Threatening but a Potential Source of Patient Harm

Example events:

- Changes in lung characteristics (compliance/resistance)
- High respiratory rates
- Auto-PEEP
- Changes in ventilatory drive (e.g., central nervous system or muscle function)

Sources: Hess D: Noninvasive monitoring in respiratory care—present, past and future: an overview, *Respir Care* 35:482–499, 1990; and MacIntyre NR, Day S: Essentials for ventilator-alarm systems, *Respir Care* 37:1108–1112, 1992.

Low-pressure alarms are usually set about 5 to 10 cm H_2O below PIP. These alarms are useful for detecting patient disconnections and leaks in the system. High-pressure alarms are set about 10 cm H_2O above PIP. High-pressure alarms can be activated when the patient coughs and if secretions increase, compliance drops, or there are kinks in the ET or circuit tubing. Low PEEP/continuous positive airway pressure (CPAP) alarms are usually set about 2 to 5 cm H_2O below the PEEP level. Activation of these latter alarms usually indicates the presence of a leak in the patient-ventilator circuit.

Apnea alarms are used to monitor mandatory or spontaneous breaths. An apnea period of 20 seconds is the highest accepted maximum. In some situations, apnea alarms are set so that the patient will not miss two consecutive machine breaths (apnea time > total cycle time [TCT] and < [TCT × 2]). Apnea settings provide full ventilatory support for the patient if apnea occurs and should be set appropriately (e.g., V_T 6–8 mL/kg ideal body weight [IBW], rate 10–20 breaths/min with a high percentage of O_2 [80%–100%]).

Most ventilators also have an alarm or indicator that alerts the operator when the inspiratory time (T_I) is more than half the set TCT. Some ventilators, such as the Servo-i will automatically end inspiration if the T_E is so short that the patient does not have time to exhale. The shortest possible T_E is 20% of any cycle time unless the patient is receiving bilevel positive airway pressure (bilevel PAP) and can be activated or inactivated.

Low-source gas alarms alert the operator that the available high-pressure gas source is not functioning. This alarm is critical for microprocessor ventilators that rely on high-pressure gas to function, particularly for ventilators that do not have a built-in compressor (Key Point 7.4).

Most ventilators also include alarms for low V_T, low and high $\dot{V}_E$, low and high respiratory rates (f), and low and high O_2 F_IO_2. Alarms should not be set so sensitively that they are constantly being triggered. The following suggestions can be used as a guide:

- Low exhaled V_T: 10% to 15% below set V_T

Key Point 7.4 Low-source gas alarms cannot be silenced if gas is critical to ventilator operation.

BOX 7.4 Alarm Failure?

An intensive care unit (ICU) patient receiving mechanical ventilatory support is on an air-filled mattress, and there is a fan in his room to help cool him. He has a pleural drainage system with suction in place.

A nurse at the ICU station hears the ECG monitor alarm, which shows a pattern of asystole. She goes to the patient's bedside, begins cardiopulmonary resuscitation, and a normal sinus rhythm is quickly restored.

The nurse notes that the patient had been disconnected from the ventilator and attributed the life-threatening event to this occurrence. The nurse also notes that when the ventilator alarm was sounding, it could barely be heard. When confronted with the nurse's concerns about alarm failure, the respiratory therapist notices that the alarm's volume adjustment is on the lowest setting and resets it to a higher volume.

This scenario occurs all too frequently in the clinical setting and represents a critical medical error that can be avoided. What would you suggest to prevent a recurrence of this situation?

- Low exhaled minute volume: 10% to 15% below-average minute volume
- F_IO_2: 5% above and below set O_2 percentage

Other alarms are available for detecting low battery levels, if the ventilator is inoperative, ventilator circuit malfunction, exhalation valve leaks, and inappropriately set parameters. For example, a set parameter (e.g., V_T) may be outside the range of the ventilator.

Unfortunately, because there are so many alarms and warning indicators on intensive care unit (ICU) equipment, many clinicians can become desensitized to audible alarms, causing the clinicians to respond slowly or not at all to these alerts.[21]

Action During Ventilator Alarm Situations

When a ventilator malfunction occurs during use, the clinician must first ensure that the patient is receiving ventilation. When in doubt, the practitioner should disconnect the patient from the ventilator and begin manual ventilation using a manual resuscitation bag, silence the alarms, and call for help. If the practitioner cannot immediately correct the problem, it may be necessary to replace the ventilator (Box 7.4). The operating manuals provided with ventilators usually have troubleshooting sections to solve most problems and can be consulted when time permits. If a ventilator problem cannot be resolved by the in-house biomedical technician support team, it will be necessary to call the local maintenance representative for the company.

PERIODIC HYPERINFLATION OR SIGHING

A *sigh* is a deep breath that occurs regularly as part of a normal breathing pattern. It is used occasionally during mechanical ventilation and related maneuvers (e.g., deep breaths or sighs are used before and after suctioning a patient) (Box 7.5).[22-30]

The sigh or deep breath was a popular idea that was introduced during the 1960s. Ventilators developed in the 1970s and 1980s incorporated sigh breaths into their designs, although traditional sigh breaths had not been shown to be clinically beneficial. These ventilators were capable of providing one or more deep breaths at periodic timed intervals (i.e., three or four times per hour or once every 10 minutes), depending on the ventilator. Because a normal sigh in a spontaneously breathing, nonintubated person occurs about every 6 minutes, ventilator manufacturers designed their machines to deliver sighs at a similar frequency.[28] Sigh volumes were set at 1.5 to 2 times the regular low V_T setting.[28] (Interestingly, low V_T settings [e.g., 5–7 mL/kg IBW] were popular at the time.)

BOX 7.5 History of Sighs and Mechanical Ventilation

Bendixen and colleagues demonstrated that anesthetized and intubated surgical patients developed increased intrapulmonary shunting, decreased P_aO_2 values, and reduced compliance after mechanical ventilation. They attributed these findings to microatelectasis from constant low tidal volumes.[22] When patients were given periodic deep breaths (sighs), these changes were reversed. Unfortunately, the effectiveness of periodic hyperinflation (sighing) continues to be debated because subsequent studies did not entirely support Bendixen's findings.[23-29] The decrease in lung compliance (C_L) and in P_aO_2 values seen in surgical patients may actually be a result of a loss of functional residual capacity in the supine position and the effects of anesthetics, muscle relaxants, and similar medications on diaphragm and intercostal muscle function. It has been suggested that this decrease in C_L and P_aO_2 can often be improved by the addition of low levels of PEEP.[29,30]

Other investigators found that large V_T (10–15 mL/kg) in anesthetized patients reduced atelectasis.[31,32] As already discussed, using these higher volumes for patients with acute respiratory failure can cause alveolar overdistention and increase the risk for ventilator-induced lung injury. Mechanical ventilator sigh breaths are therefore *not* recommended in the presence of P_{plat} pressures greater than 30 cm H_2O.

Mild hypoxemia sometimes occurs in patients receiving pressure support ventilation (PSV) with low volumes (4–6 mL/kg). Studies of the use of sigh breaths in these patients may be worth examining.[29] However, sigh breaths are not indicated for these patients and may be harmful to spontaneously breathing patients receiving CPAP for the treatment of hypoxemia.[33]

With the advent of low V_T strategy in patients with ARDS, another ventilator strategy called *lung recruitment* has been successfully used in selected patients.[34,35] The recruitment maneuver is not unlike sigh breaths. The recruitment maneuver, which is used to expand collapsed areas of the lung, involves using a sustained high pressure of 35 to 45 cm H_2O for 40 to 60 seconds.[35-37] Interestingly, the sigh breaths used by Bendixen and colleagues in 1963,[22] more than 50 years ago, were as follows:

- One breath at 20 cm H_2O for 10 seconds
- A second breath at 30 cm H_2O for 15 seconds
- A third breath at 40 cm H_2O for 15 seconds

These sustained high-pressure maneuvers are not unlike the recruitment maneuvers that are used in the management of patients with ARDS (Key Point 7.5).

Key Point 7.5 When low tidal volumes are used, such as in patients with acute respiratory distress syndrome, a recruitment maneuver may be an effective method to avoid atelectasis.

Sighs or deep breaths may be appropriate in the following situations:

- Before and after suctioning
- Before and after bronchoscopy
- During an extubation procedure
- During chest physiotherapy
- During low V_T ventilation
- As a recruitment maneuver in some patients with ARDS

FINAL CONSIDERATIONS IN VENTILATOR EQUIPMENT SETUP

Before initiating mechanical ventilation, the respiratory therapist should perform a final check of the equipment to be used. This check should include the following steps:

- Check ventilator and circuit function to ensure the ventilator is functioning properly and no significant leaks are present.
- Ensure the humidifier is filled with sterile water and set the humidifier temperature so that the final gas temperature at the airway will be approximately 31° to 35° C or place an HME in line.
- Place a temperature-monitoring device near the patient connector when heated humidification is used.
- Check the F_IO_2, set V_T (or inspiratory pressure) and f.
- Adjust the alarms.
- Ensure the patient is connected to an electrocardiographic monitor.
- Have an emergency airway tray available at the bedside in case the patient's airway is removed or damaged.
- Check that suctioning equipment is available and functioning.
- Select a volume-monitoring device and an O_2 analyzer if one is not available with the ventilator.
- Ensure that a manual resuscitation bag is available and easily accessible.

Once the decision has been made to connect the patient to a ventilator, several steps should be taken, including the following:

- Preparing the patient
- Establishing an airway interface
- Providing manual ventilation to the patient
- Ensuring the patient's cardiovascular status is stable
- Meeting ventilation needs
- Treating the cause of respiratory failure

Preparing the Patient

Mental preparation of a patient who will require mechanical ventilation is an obvious part of preoperative planning for patients who will likely need short-term postoperative ventilatory support. It is an important part of patient preparation because it can significantly reduce the patient's anxiety and discomfort.

Before initiating mechanical ventilation, conscious patients must be prepared for what to expect once they are connected to the ventilator. The clinician should give a brief explanation about how the ventilator works and why it is being used. The patient also must be informed that the use of an artificial airway will inhibit verbal communication.

Unconscious patients should be informed about their situation as soon as they regain consciousness. This is crucial because these patients will be unable to speak and may be completely unaware of what has occurred. Often the explanation will need to be repeated because sedatives and similar agents can alter a patient's mental status.

Establishing an Interface

For noninvasive ventilation, a face or nasal mask is properly fitted (see Chapter 19). During invasive ventilation, the three most commonly used artificial airways are orotracheal, nasotracheal, and tracheostomy tubes. Orotracheal tubes are used for emergencies and are generally kept in place for several days. Nasotracheal tubes provide better patient comfort but may require more insertion time. Nasotracheal tubes usually have smaller diameters than orotracheal tubes and are associated with increased incidence of sinus infections. Tracheostomy tubes must be inserted surgically, but these tubes can be used for extended periods. They also allow for easier pulmonary hygiene and are apparently most comfortable for the patient, even allowing the patient to talk in some cases.

Manual Ventilation

Before initiating mechanical ventilation, the patient's ventilatory requirements can be supported by using a manual resuscitation bag. These devices are easy to operate and allow the clinician to monitor closely the patient's breathing efforts and changes in airway resistance (R_{aw}) or lung compliance (C_L).

Cardiovascular Stabilization

The combined stress of acute or impending respiratory failure and endotracheal intubation can reveal undiagnosed cardiovascular complications that may already be present. For example, patients with existing or borderline myocardial ischemia may develop cardiac dysrhythmias. The effects of any of the pharmacological agents used during intubation (e.g., topical anesthetics, sedatives, narcotics, and muscle-paralyzing agents) can lead to hypotension and relative hypovolemia, resulting in reduced venous return and cardiac output. Appropriate cardiovascular support is therefore essential to a successful outcome.

Ventilator Needs

After the patient's cardiovascular status is stabilized and primary ventilatory needs are being met, the clinician can then select the appropriate mechanical ventilator mode and appropriate ventilator settings (see Chapter 6).

Treating the Cause of Respiratory Failure

Once a life-threatening situation no longer exists, attention can be turned to treating the initial problems that caused the patient to require ventilation. Mechanical ventilation is not curative; the underlying problem must be resolved regardless of whether it is the result of central nervous system or neuromuscular problems or increased WOB caused by trauma, ARDS, or COPD with complications. It makes little sense to be overly aggressive with palliative methods if the underlying pathologic process is irreversible.

SELECTING THE APPROPRIATE VENTILATOR

Specific ventilator selection depends on not only theoretical but also practical considerations. The ventilators available at an institution and the familiarity of personnel with this equipment usually determine ventilator choice. Detailed descriptions of many available ventilators and their features are available from other sources.[38]

The selected ventilator should offer a variety of modes of ventilation, including volume-controlled or pressure-controlled

continuous mandatory ventilation (VC-CMV or PC-CMV), volume-controlled or pressure-controlled intermittent mandatory ventilation (VC-IMV or PC-IMV), and spontaneous CPAP/PSV.

Adult ventilators are typically capable of delivering V_T in the range of 100 to 2000 mL and respiratory rate from 1 to 60 breaths/min. Pressures from 0 to 100 cm H_2O are adequate, and the driving pressure must be high enough to maintain the gas flow pattern throughout inspiration regardless of how high peak pressures may rise. PEEP/CPAP should be in the range of 0 to 30 cm H_2O. Flow rates should range from 10 to 180 L/min. Constant (square/rectangular) flow or descending flow patterns probably have more clinical benefit than others and should be included.[37] An inspiratory-to-expiratory (I/E) ratio display may be useful in the management of patients who are difficult to oxygenate.

Response time, patient circuits, exhalation valves, PEEP, and demand valves should be designed to reduce WOB and patient resistance to inspiration and expiration. Two important ventilatory adjuncts are inflation hold and expiratory pause. Inflation hold is used to measure P_{plat}, which is used to calculate static compliance. Expiratory pause is used for auto-PEEP measurements.

The mechanical ventilator should be able to deliver F_IO_2 values from 21% to 100% in increments of 1% to 2%. Alarms should include apnea, pressure limit, power failure, gas source, and low- and high-pressure alarms. If available, high f, low V_T, and high and low $\dot{V}_E$ alarms are particularly important for monitoring pressure-targeted ventilation and spontaneous modes such as PC-CMV, PC-IMV, CPAP, and PSV.

It is important to recognize that these are the fundamental features of adult ventilators, not a description of an ideal ventilator. In fact, most microprocessor ventilators may be equipped with additional modes and features.

EVALUATION OF VENTILATOR PERFORMANCE

The cost of purchasing a particular ventilator and the specific needs of the patients served by the institution should be considered before purchasing a new ventilator—specifically, whether these patients will require short- or long-term ventilation. The needs of the medical staff should also warrant consideration. For example, the amount of in-service training that will be required to ensure that the respiratory therapy staff is proficient in the use of the equipment should be part of the selection process.

A performance evaluation, or bench test, must be conducted on every ventilator brand before purchase and certainly before patient connection. Forms for conducting these tests are available from the Joint Commission and American National Standards Institute. A bench test requires the use of a lung analog, which can simulate alterations in respiratory system function. Instruments for measuring volume, pressure, flow, and time are also needed. Bench tests examine ventilator performance during changes in compliance and resistance and leak conditions and check general features, parameter ranges, and alarm systems. These tests must also account for various simulated conditions, such as very low and very high $\dot{V}_E$ values, air trapping (auto-PEEP), function during added nebulization, and CPAP function.

Once purchased, ventilators must be checked regularly with maintenance, testing, and calibration programs. Records must be maintained for each ventilator, as well as documentation of personnel training for ventilator use.

Initial Ventilator Settings for Specific Patient Situations

The following cases offer the reader some guidance for making initial ventilator settings. The study questions at the end of the chapter provide additional practice in this area.

A number of published reviews along with several other textbooks provide information about currently accepted practices for managing various pulmonary disorders requiring mechanical ventilation.[3-5,40-43] The settings recommended in the following cases reflect the standard of practice suggested by these sources.

CHRONIC OBSTRUCTIVE PULMONARY DISEASE

Patients with COPD have increased R_{aw} and may also have increased C_L, which, when combined, cause significant expiratory obstruction, lengthen the time constant, and lead to air trapping. When patients with COPD require mechanical ventilation, it is often because their chronic disease has been coupled with another problem, such as a respiratory infection, leading to acute-on-chronic respiratory failure.

Mechanical ventilation in COPD is associated with increased morbidity because of air trapping, nosocomial infections, barotrauma and volutrauma, cardiac problems, aspiration, and difficulty weaning. The goals of mechanical ventilation are to maximize patient-ventilator synchrony, reduce WOB and patient anxiety, and avoid the complications associated with mechanical ventilation, such as ventilator-associated pneumonia and ventilator-induced lung injury.

Guidelines for Patients With Chronic Obstructive Pulmonary Disease

Basic guidelines for mechanically ventilating patients with COPD have been established.[3-5,40-45] These guidelines include the following:

- If possible, use noninvasive ventilation to avoid problems associated with artificial airways. Bilevel positive airway pressure (bilevel PAP) is ideal for patients with chronic pulmonary disorders (see Chapter 19).
- If intubation is necessary, an orotracheal intubation is recommended.
- The clinician can select a ventilator mode that he or she thinks is most familiar. It has been noted, however, that VC-CMV or PC-CMV may unload the work of the respiratory muscles more than IMV.[44] Using patient-triggered CMV in an alert patient with COPD may increase the risk for hyperinflation and elevated lung pressures. This mode should be monitored carefully.[44]
- Adjust the peak inspiratory flow to meet the patient's demand in VC-CMV using the descending flow pattern: flow greater than 60 L/min.
- In patients with COPD and asthma, in whom airway obstruction and resistance are high, an initial V_T of 6 to 8 mL/kg with a rate of 8 to 16 breaths/min and T_I 0.6 to 1.2 seconds is acceptable.
- PEEP of 5 cm H_2O or lower, or about 50% of auto-PEEP, should be used initially.
- Monitor for and minimize dynamic hyperinflation (auto-PEEP) by setting the lowest possible $\dot{V}_E$ that produces acceptable gas exchange, targeting the patient's baseline P_aCO_2 and pH_a.

- Provide the longest expiratory time (T_E) possible. This may include decreasing T_I, increasing T_E, reducing f or V_T, and accepting hypercapnia (P_aCO_2 higher than the patient's normal). (NOTE: Patients with COPD usually receive ventilation in their normal P_aCO_2 range [e.g., P_aCO_2 = 50–60 mm Hg; pH 7.3–7.4].)
- If the patient is initiating inspiration once ventilation has started and auto-PEEP is present, set PEEP near 80% of the auto-PEEP level but do not exceed it (3–5 cm H_2O is often adequate). If PIP begins to rise because PEEP is increased, the safe PEEP level has probably been exceeded and will result in lung overinflation. Several other strategies that may be used to address the issue of auto-PEEP include decreasing the inspiratory time, increasing the peak flow, and administering a bronchodilator.
- P_{plat} should be monitored and maintained below 30 cm H_2O to avoid alveolar overdistention and, consequently, lung injury. Accurate measurement of P_{plat} may require sedation and paralysis. The decision to medicate patients is generally based on physician preference and institutional policy.
- Maintain P_aO_2 at 55 to 75 mm Hg or near the patient's normal P_aO_2, with F_IO_2 less than 0.5, unless the patient's condition worsens and he or she requires more O_2.

PC-CMV may be ideal for this group of patients for several reasons. PC-CMV provides flow on demand to meet the patient's needs. T_I can be set along with a backup rate, but patient triggering is still permitted. PC-CMV has a distinct advantage over PSV for this patient population because inspiration during PSV can be too long or too short, depending on the patient's active breathing patterns. This can result in increased WOB and poor patient-ventilator synchrony. Auto-PEEP can be a lethal complication. Current ventilators that allow an adjustable expiratory flow cycle may allow for the use of PSV in COPD.

Volume-assured pressure support or volume support (Servo-i) can also provide pressure ventilation with a set targeted volume delivery. Although these modes are also well suited for patients with COPD, clinicians must be familiar with their use.

An important part of patient care is providing adequate hydration and pharmacological therapy (i.e., bronchodilators and corticosteroids) to reverse airflow limitation. Secretions must be mobilized and removed, and if infections are present, appropriate antibiotic therapy must be administered. The primary problem necessitating ventilation must be corrected to ensure weaning will be successful. Because many of these patients are malnourished, an evaluation of their nutritional needs must be part of any follow-up program.

Clinical Scenario: Chronic Obstructive Pulmonary Disease

A 65-year-old man with a history of COPD is brought to the emergency department (ED) complaining of severe shortness of breath. The following information was obtained during an initial patient assessment. The S_pO_2 of 75% obtained while he was breathing room air is low. Because pulse oximetry may be inaccurate in this range, an ABG was obtained. A 28% air-entrainment mask was placed on the patient.

Initial Patient Assessment on Admission: History of COPD

The patient is a retired salesman and lives at home with his wife. He has a 40-pack-year history of cigarette smoking.

Mental Status

- Alert and oriented but shows signs of fatigue
- Speaks in halting sentences and appears to be catching his breath between efforts to talk

Physical Appearance

- Tall and thin
- Barrel chest
- Pale skin
- Pitting edema of the ankles
- Prolonged expiration through pursed lips with labored breathing
- Sitting in a chair, leaning forward with his arms on the chair arms
- Active use of the sternocleidomastoid muscles

Vital Signs

- f = 35 to 40 breaths/min
- Heart rate = 135 beats/min
- Blood pressure = 185/110 mm Hg
- Temperature = 37° C

Breath Sounds

- Bilateral wheezes, crackles in the bases, hyperresonance to percussion bilaterally

Cough

- Weak, producing a moderate amount of thick, yellow secretions

S_pO_2

- 75% on room air

Chest Radiograph

Increased bilateral radiolucency, flattened diaphragm, widened rib spaces; scattered infiltrates in both bases.

The patient is given an aerosol treatment with albuterol by small-volume nebulizer followed by an aerosolized mucolytic. He does not tolerate the treatment well and is unable to take a deep breath or perform a breath-hold maneuver. His dyspnea persists. ABGs on an F_IO_2 of 0.28 are pH_a = 7.24; P_aCO_2 = 97 mm Hg; P_aO_2 = 38 mm Hg; and HCO_3- = 41 mEq/L.

The ABGs indicate chronic CO_2 retention (elevated HCO_3-) that has now progressed to an acute-on-chronic phase (elevated P_aCO_2 and low pH_a). His ABG results indicate severe hypoxemia. The infiltrates in the lower lung fields and the production of thick yellow sputum suggest the presence of a respiratory infection, but the absence of an elevated temperature is confusing. (NOTE: Elderly patients, particularly those with chronic health problems, do not always develop a fever. If patients take aspirin or nonsteroidal or steroidal antiinflammatory medications, an elevated temperature may be masked.) A sputum specimen is sent to the laboratory for culture and sensitivity testing.

On the basis of the assessment, a decision is made to begin mechanical ventilatory support. The patient is 5-ft, 10-in tall and weighs 148 lb. What are his body surface area (BSA) and IBW? What initial settings for $\dot{V}_E$, f, T_I, and flow would be appropriate? Would you use pressure or volume ventilation?

The following section answers these questions and provides the initial settings selected in this case.[45]

Initial Ventilator Settings: COPD Patient

- BSA = 1.85 m^2
- IBW = 106 + 6 (10) = 166 lb (75.5 kg)
- Initial $\dot{V}_E$ = 4 × 1.85 = 7.4 L/min
- Because of concern for air trapping, consider a lower set $\dot{V}_E$.
- Attempt to synchronize the ventilator with the patient.
- Noninvasive ventilation is appropriate.

A Philips Respironics BiPAP ventilator is selected. With this ventilator, a low level of CPAP/PEEP (2 cm H_2O) is maintained in the airway even when the expiratory positive airway pressure (EPAP) control is minimal.

- Rate is set at 8 breaths/min, TCT = 60/8 = 7.5 seconds, and T_I = 13% of TCT
- I/E ratio = 1:6.5, T_I = 1.0 seconds, and T_E = 6.5 seconds
- Inspiratory positive airway pressure (IPAP) = 10 cm H_2O initially and is titrated to obtain an exhaled V_T of 600 mL (0.6 L).
- Final IPAP is 14 cm H_2O.
- EPAP = set at 4 cm H_2O
- Spontaneous/timed setting is selected, providing a backup rate, at which point time-triggered breaths are modified pressure control (PC) breaths; spontaneous breaths are pressure support (PS) breaths.
- O_2 is titrated to ≥90% O_2 saturation measured by pulse oximetry (S_pO_2).

The patient is transferred to the ICU, and the settings are maintained for 2 hours. It becomes increasingly difficult for the patient to clear secretions, and he continues to try to remove the mask. He eventually consents to intubation and is intubated using a size 8-Fr orotracheal ET. The physician asks the respiratory therapist to maintain similar settings but wants to use Dräger Evita Infinity V500 in the VC-CMV mode. The following section shows the selected ventilator settings.

VC-CMV Settings: Patient With COPD

- Pressure required during inspiration was 14 cm H_2O
- PEEP at 4 cm H_2O, as previously present
- Set rate at 8 breaths/min
- V_T (set) of 600 mL (0.6 L) to match previous setting
- Flow at 80 L/min to start
- Flow waveform is constant (the current recommended setting for this mode)
- F_IO_2 at 0.3 to 0.5, because exact setting is unknown; titrate to achieve SpO_2 of ≥90%
- The following information is noted after assessment:
  - The patient triggers every breath but at a rate above 8 breaths/min. TCT is about 2.5 seconds.
  - T_I is about 1 second and T_E is about 1.5 seconds.
  - Expiratory flow does not return to zero before the next breath, indicating the presence of auto-PEEP.
  - During inspiration, following an initial high flow, flow drops to 80 L/min and stays there until V_T is delivered.
- This flow may not be adequate to keep T_I short.
- Possible solutions to minimize air trapping may include:
  - Switching to PC-CMV with a short T_I.
  - Setting a lower V_T.
  - Checking the patient's airway to be sure it is clear of secretions and possibly administering a bronchodilator.
  - Increasing inspiratory flow.

Appropriate adjustments are made, and the patient is successfully managed using PC-CMV. The respiratory infection is resolved 5 days later. Secretion clearance is improved. Occasional scattered crackles are heard on auscultation, but otherwise breath sounds have cleared. Infiltrates are no longer present on chest radiographs. Weaning should now be considered for this patient.

ASTHMA

Patients presenting an exacerbation of **acute severe asthma** that requires mechanical ventilation are among the most difficult to manage. Increased R_{aw} from bronchospasm, increased secretions, and mucosal edema increase the incidence of air trapping. Trapped air can cause uneven hyperexpansion of various lung units, which can rupture or compress other areas of the lungs, leading to pneumothorax, pneumomediastinum, subcutaneous emphysema, and other forms of **barotrauma.**

During an asthma exacerbation, the patient struggles to breathe while trying to move air against increasing airway resistance. The result is dramatic changes in intrapleural pressures (P_{pl}) during inspiration and expiration that affect gas distribution in the lungs and also alter cardiac function, resulting in **pulsus paradoxus.** Progressive hypoxemia further enhances the patient's drive to breathe and compounds anxiety. Even aggressive treatment with bronchodilators and steroids might not be enough to reverse the course of an acute asthma exacerbation.

Box 7.6 lists indications for mechanical ventilation for this group of patients. The primary goal during mechanical ventilation of these patients is to focus on reversing the high R_{aw} while avoiding or reducing air trapping. If the patient has anxiety and the drive to breathe produces patient-ventilator asynchrony during

BOX 7.6 Indications for Mechanical Ventilation in Acute Exacerbation of Asthma

1. Exhaustion (e.g., respiratory rate progressively decreases and level of consciousness is altered), with developing metabolic acidosis and decreasing pH in the presence of a normal or rising CO_2 pressure (P_aCO_2).
2. If audible, bilateral wheezes become distant as air trapping increases (e.g., breath sounds absent, chest hyperresonant to percussion or fixed on palpation).
3. Severe hypoxemia while receiving O_2 (e.g., inability to oxygenate with supplemental O_2).
4. Chest radiograph with depression of the hemidiaphragms and increased radiolucency, suggestive of air trapping.
5. Altered mental status, confusion, or decreased level of consciousness.
6. Life-threatening dysrhythmias.
7. P_aCO_2 rises while pH declines (e.g., ≥40 mm Hg; pH ≤7.25 [progressive respiratory acidosis superimposed on metabolic acidosis]).
8. Cardiac or respiratory arrest.

mechanical ventilation, sedation and possibly paralysis may be required. (NOTE: The use of certain paralytics may result in a neuropathy that can produce prolonged paralysis, which can hinder weaning from ventilatory support. Indeed, prolonged paralysis can have long-term effects, such as reducing a patient's ability to ambulate for several weeks or months. [This can be a particularly serious complication in patients with renal insufficiency or hepatic disease, particularly when paralytic agents and corticosteroids are used in combination for extended periods.])

Guidelines for Patients With Asthma

The following guidelines provide suggestions for mechanically ventilating patients with asthma.[3-5,41-43,45-50]

- VC-CMV and PC-CMV are acceptable modes immediately after intubation. It is easier to control airway pressure with PC-CMV.
- Maintain peak and plateau pressures at minimal levels. PIP may be high because of the high R_{aw} and the use of high inspiratory gas flows. Alveolar (plateau) pressures must still be maintained at less than 30 cm H_2O despite the high PIP.
- Ensure that the patient's oxygenation status is adequate by using an F_IO_2 as needed to achieve a P_aO_2 from 60 to 100 mm Hg (usually F_IO_2 $\geq$0.5). Monitor hemodynamic status to ensure cardiac output is stable.
- Permissive hypercapnia (P_aCO_2 45–80 mm Hg) is acceptable as long as pH is acceptable (i.e., $\geq$7.2). (NOTE: Tris-hydroxymethyl-aminomethane or bicarbonate is administered by some physicians to keep pH >7.2. The preference between these agents varies among physicians.)
- If the ventilator settings cannot accommodate the patient's needs, the use of sedatives and paralytics may be necessary. The use of sedation and paralysis may permit resting of fatigued respiratory muscles, particularly during the first 24 hours.[46]
- When patients are spontaneously breathing and having trouble triggering breaths, setting the $PEEP_E$ at about 80% of intrinsic PEEP may allow for easier triggering of ventilator breaths. (NOTE: $PEEP_E$ is indicated in only a few situations, because these patients already have an increased functional residual capacity.) In some cases, applied PEEP may recruit lung units that are collapsed (even in the presence of auto-PEEP) and may also assist with expired gas flows.[51] In other cases it may worsen the patient's condition. If PIP increases with the application of $PEEP_E$, decrease the level of $PEEP_E$.
- Reduce the incidence of air trapping by providing long expiratory times:
  - f = <8 breaths/min; V_T = 6 to 8 mL/kg; T_I = $\leq$1 sec; inspiratory gas flow = 80 to 100 L/min descending flow waveform.[51]
- The occurrence of barotrauma in the form of pneumothorax, for example, is not uncommon in these patients. Regular assessment of breath sounds and diagnostic chest percussion, along with chest radiographs, can help guide therapy to avoid this potential problem.

Clinical Scenario: Patient With Asthma

A 13-year-old girl with a history of severe persistent asthma is brought to the ED at 2:30 a.m. Wheezing is audible without the use of a stethoscope. Auscultation of the chest confirms that the wheezing is bilateral. The patient has used her albuterol MDI 10 times (20 puffs) in the past 4 hours. Current peak expiratory flow rate (PEFR) is 150 L/min. A chest radiograph shows increased radiolucency and depressed hemidiaphragms. ABGs on a 2-L/min nasal cannula are pH = 7.43; P_aCO_2 = 25 mm Hg; P_aO_2 = 43 mm Hg; HCO_3- = 17 mEq/L. Her S_pO_2 is 73%. She is started on bronchodilators (albuterol and Atrovent) via continuous aerosol and intravenous corticosteroids (Solu-Medrol).

The patient's condition does not improve over the next 5 hours, in spite of therapy. Her breath sounds are more distant, and there is hyperresonance to percussion of the chest wall. She is cyanotic and anxious, and her breaths are labored. On a 4-L/min O_2 nasal cannula, ABGs are pH = 7.25; P_aCO_2 = 59 mm Hg; P_aO_2 = 53 mm Hg; HCO_3- = 25 mEq/L. S_pO_2 is 79%. PEFR is 120 L/min and f is 16 breaths/min (down from 30 breaths/min on admission). Blood pressure is 160/100 and heart rate is 175 beats/min. She is transferred to the ICU, and the decision is made to intubate her and begin mechanical ventilatory support. To calculate initial settings, see the following section.

Initial Ventilator Settings: Patient With Acute Asthma

On the basis of this patient's history and size (5 ft, 3 in [63 in], 108 lb [49 kg]):

- IBW = 105 + 5(3) = 120 lb (54.5 kg)
- BSA = 1.5 m^2
- Initial $\dot{V}E$ = 1.50 × 3.5 = 5.25 L/min
- Targeted V_T (6–8 mL/kg); 327 to 435 mL
- f = $\dot{V}E/V_T$ = (5.25 L/min)/0.435 L = 12 breaths/min.

NEUROMUSCULAR DISORDERS

It is not unusual for patients with neuromuscular disorders to require ventilatory support. Examples of disorders that are included in this category are myasthenia gravis, amyotrophic lateral sclerosis, muscular dystrophy, Guillain-Barré syndrome, tetanus, cervical spinal cord injury, postpolio syndrome, and botulism. Patients with ventilatory failure because of a neuromuscular disorder usually have a normal ventilatory drive and normal or near-normal lung function. Most of the neuromuscular disorders cited cause respiratory muscle weakness, which can limit these patients' abilities to cough and clear secretions. As a result, they tend to develop atelectasis and pneumonia. If the glottic response is weak, they may also have an increased risk for aspiration. Mechanical ventilation is most often required if progressive respiratory muscle weakness will eventually lead to respiratory failure.

Patients with neuromuscular problems can be effectively ventilated with either positive or negative pressure ventilation. In the hospital environment, positive pressure ventilation is most often selected and can be either noninvasive or invasive. Negative pressure ventilation is rarely used.

The patients most often seen in hospitals are those with a rapid onset of their disease that requires admission (e.g., Guillain-Barré syndrome, myasthenia gravis). Because these patients often have normal lung function, they are at low risk for barotrauma and are most comfortable when ventilated with higher V_T values (i.e., 6–8 mL/kg) and high inspiratory flow rates greater than 60

L/min using a constant flow or descending flow pattern when VC-CMV is used. (NOTE: Some clinicians prefer starting with a lower V_T and adjusting the volume as needed.) Patients with spinal cord injuries resulting in quadriplegia require full ventilatory support. Patients with myasthenia gravis usually require only partial support until their own breathing capacity returns.

Guidelines for Patients With Neuromuscular Disorders

The following guidelines are recommended for mechanically ventilating patients with neuromuscular disorders[3-5,41-42]:

- Full or partial support
- Positive or negative pressure ventilation
- Noninvasive or invasive ventilation
- VC-CMV
- V_T (6–8 mL/kg) while maintaining the Pplat at less than 30 cm H_2O
- f = 8 to 16 breaths/min
- Inspiratory flow rates ≥60 L/min to meet patient need (T_I ~1 second to start)
- Flow waveform: Constant or descending flow pattern
- PEEP = 5 cm H_2O may be needed to relieve dyspnea
- F_IO_2 = 0.21

Clinical Scenario: Neuromuscular Disorder

A 5-ft, 2-in, 115-lb, 67-year-old woman with a history of myasthenia gravis was brought to her physician's office by her daughter. She complained of progressive muscle weakness. Physical examination revealed that she demonstrated drooping eyelids and difficulty talking and swallowing. She was unable to walk more than a step or two. She was transferred to the hospital, where she was given edrophonium (Tensilon), which improved her muscle function for 10 to 15 minutes. On admission, her vital signs were unremarkable. Her maximum inspiratory pressure (MIP) was −35 cm H_2O, and her vital capacity (VC) was 1.8 L (predicted was 3.3 L). Her S_pO_2 on room air was 96%.

Anticholinesterase therapy was administered, and MIP and VC were monitored every 8 hours. The nursing staff reported that the patient was having trouble swallowing when she ate and they feared that she would aspirate. MIP and VC values progressively declined. After being hospitalized for 24 hours, her MIP was −25 cm H_2O and VC was 1.0 L. ABGs on room air were pH = 7.36; P_aCO_2 = 48 mm Hg; P_aO_2 = 62 mm Hg; HCO_3^- = 27 mEq/L. The following section provides a summary of the therapeutic intervention used for this patient. Could noninvasive positive pressure ventilation (NIV) be used in this situation?

Initial Ventilator Settings: Patient With Neuromuscular Disorder (Myasthenia Gravis)

The patient was intubated because of increased risk for aspiration. (Invasive mechanical ventilation was initiated rather than NIV because her ability to swallow was compromised and she showed signs of acute respiratory failure despite anticholinesterase therapy.)

The patient is 5-ft, 2-in tall and weighs 115 lb, so:

- IBW = 105 + 5(2) = 115 lb (52 kg)
- BSA is 1.5 m^2
- Estimated $\dot{V}E$ is 3.5 × 1.5 = 5.25 L
- V_T = 420 mL (8 mL/kg) (VC-CMV)
- Rate = 13 breaths/min
- Flow = 60 L/min using a constant waveform
- PEEP = 2 cm H_2O and F_IO_2 = 0.21
- Calculate T_I and T_E
- T_I = VT/flow (L/s) = 0.420 L/(1 L/s) = 0.42 second
- TCT = 60 s/12 = 5.0 seconds
- T_E = 6.0 − 0.42 = 5.58 seconds
- PIP = 20 cm H_2O
- Pplat = 12 cm H_2O
- What is the transairway pressure? 20 − 12 = 8 cm H_2O
- What is the patient's C_L and is it normal?
  - $C_L = V_T/(P_{plat} - PEEP) = 0.420/(12 - 3) = 0.046$ L/cm H_2O or 46 mL/cm H_2O
  - C_L is normal

Ventilatory support was maintained for a total of 10 days, with one occurrence of a respiratory infection that responded to antibiotic therapy. She was successfully weaned and extubated on the 10th day.

CLOSED HEAD INJURY

Closed head injury is an injury to the brain in which the skull remains intact. It is most commonly caused by trauma to the head from falls, automobile accidents, and blows to the head. Because the skull is a closed container, bruising the brain tissue can result in swelling (edema) and increased intracranial pressure (ICP). Similar effects may occur after surgery (postcraniotomy), medical accidents (i.e., cerebrovascular accident [stroke], and post-resuscitation hypoxemia.)[3,37,41,42]

The cranial vault contains the brain, blood, and cerebrospinal fluid. Assessment of cerebral blood flow is important because the brain relies on steady blood flow to provide O_2. Maintaining sufficient cerebral blood flow requires an adequate cerebral perfusion pressure (CPP). CPP is defined by this equation: CPP = mean arterial pressure (MAP) − ICP. Normal values for MAP are 90 to 95 mm Hg and ICP less than 10 mm Hg. Normal CPP is 80 to 85 mm Hg. Values of CPP lower than 60 mm Hg indicate poor cerebral perfusion.

Clinically, it is important to keep ICP low and MAP in the normal range to maintain CPP in brain-injured patients. Several techniques can be used to accomplish this goal. Mannitol infusion can be used to increase osmotic pressures and reduce ICP in acute situations; diuretics can reduce fluid volume (may reduce MAP, which may reduce CPP); and barbiturates can be used to reduce cerebral O_2 demand and lower ICP when conventional therapy fails. Patients should be maintained with their head in a neutral position and the head of the bed elevated by 30 degrees.

Iatrogenic hyperventilation, or the deliberate lowering of P_aCO_2, is sometimes used to reduce ICP, but its effectiveness remains controversial. The theory is that acute reductions in P_aCO_2 are thought to result in cerebral vasoconstriction, reducing cerebral blood volume and ICP. (NOTE: a decreasing CO_2 is associated with an increase in pH.) The effect of CO_2 and pH change on ICP is most pronounced when it is acute and loses its effect as the pH of the cerebrospinal fluid becomes normalized. Therefore P_aCO_2 should be normalized as soon as possible, depending on ICP response. It is important to mention that not all physicians

BOX 7.7 Indications for Mechanical Ventilation in Patients With Head Injuries

Assisted Ventilation
1. Respiratory depression associated with injury. It may be manifested as Cheyne-Stokes respiration, central neurogenic hyperventilation, or apnea.
2. Additional injuries to the chest, abdomen, back, or neck.
3. Use of medications that depress respiration.
4. Neurogenic pulmonary edema (an acute respiratory distress syndrome–like pattern that can occur after head trauma).
5. Impending or actual cardiac arrest.
6. Upper airway compromise (e.g., presence of stridor or loss of airway clearance mechanisms).
7. Aspiration at the time of loss of consciousness.

Airway Management (Intubation)
1. Head injury (particularly with Glasgow Coma Scale score* of ≤8).
2. Face, jaw, neck injuries with bleeding.

Oxygen Delivery
1. Head injury.
2. Pulmonary contusion, edema, or both.

*See Box 7.8.

BOX 7.8 Glasgow Coma Scale Score*

Verbal Response
1 = None
2 = Incomprehensible sounds
3 = Inappropriate words
4 = Confused
5 = Oriented

Eye Opening
1 = None
2 = To pain
3 = To speech
4 = Spontaneously

Motor Response
1 = None
2 = Abnormal extension to pain
3 = Abnormal flexion to pain
4 = Withdraws from pain
5 = Localizes pain
6 = Follows commands

*The Glasgow Coma Scale score evaluates a patient's verbal, eye, and motor responses. Scores range from 3 to 15.

advocate the use of this technique. Furthermore, if an increased ICP is not present, iatrogenic hyperventilation is not indicated (current standards suggest that the P_aCO_2 should be maintained between 35 and 40 mm Hg). When a high ICP is present, iatrogenic hyperventilation can be used for a short time. Box 7.7 lists the indications for mechanical ventilation in patients with head injury.[3] Box 7.8 provides information on the Glasgow Coma Scale score mentioned in Box 7.7.

Guidelines for Patients With a Closed Head Injury

The following guidelines are recommended for mechanically ventilation in patients with closed head injuries[3-5,41-42]:

- After head injury, protect the airway because patients with altered levels of consciousness may be unable to do so. There is a high risk for vomiting and aspiration. Orotracheal intubation is often required.
- PC-CMV and PEEP can actually increase ICP. These patients often have normal lungs, so high P_{alv} can be transmitted to the blood vessels, thus affecting venous return from the head. Monitoring for elevated ICP can help evaluate this effect.
- Monitor for increased ICP and hypoxemia so that a rapid increase in ventilation and oxygenation can be instituted if needed or if recommended by institutional policy.
- When there is acute uncontrolled increased ICP, maintain P_aCO_2 from 25 to 30 mm Hg or titrate the ICP if it is being monitored.
- If iatrogenic hyperventilation is used, this should be only temporary, with P_aCO_2 gradually returning to normal levels in 24 to 48 hours, allowing acid-base balance to restore itself. Sudden increases in P_aCO_2 could trigger increases in cerebral blood flow and ICP. A normal response to acute increases in ICP is hypertension with bradycardia, which is called the **Cushing response.**[3]
- Ventilator settings include the following:
  - Provide full ventilatory support to start.
  - Either PC-CMV or VC-CMV can be used.
  - Maintain V_T from 6 to 8 mL/kg IBW while maintaining P_{plat} less than 30 cm H_2O.
  - An f of 15 to 20 breaths/min to provide normal acid-base status, as long as auto-PEEP is avoided.
  - $F_IO_2 = 1.0$ initially and titrate as needed to keep P_aO_2 from 70 to 100 mm Hg to avoid hypoxemia.
  - High inspiratory flow (>60 L/min) to keep T_I short, about 1 second (avoid auto-PEEP) using a descending ramp pattern or constant flow pattern.
  - PEEP = ≤5 cm H_2O, as long as ICP is being measured and is ≤10 mm Hg. Because PEEP can increase ICP, it is used only if necessary to avoid severe hypoxemia.
- Suctioning and chest physiotherapy can dramatically increase ICP, but maintaining a clear airway is also essential. Consequently, bronchial hygiene therapy must be done with extreme caution.
- Monitor for complications of pulmonary infections and pulmonary emboli.

Clinical Scenario: Acute Head Injury

A 23-year-old man is admitted to the ED after hitting his head against a tree in a skiing accident. He is unconscious on admission. There are no fractures to his head, neck, thorax, or limbs, but some bruising is present on his arms and legs. On admission, his vital signs are blood pressure = 150/90 mm Hg; heart rate = 110 beats/min and regular; f = 12 breaths/min; and temperature = 35.6° C. Breath sounds are equal and clear bilaterally. He withdraws from painful stimuli but is otherwise unresponsive. His pupils respond equally to light.

The decision is made to intubate the young man to protect his airway. A computed tomogram of the head reveals an intracranial hemorrhage. After neurosurgery, the patient is transferred to the ICU; an ICP monitor is in place, along with an arterial line and a pulmonary artery catheter. He is receiving phenobarbital (a barbiturate) and midazolam (a short-acting benzodiazepine). The patient is 6 ft, 4 in (76 in) and weighs 225 lb (102 kg). ICP is 15 mm Hg, and hemodynamic data are within normal limits. The following section provides suggestions for his initial ventilator setting.

Suggesting Initial Ventilator Settings: Patient With Head Injury

- Patient's IBW: 106 + 6(16) = 202 lb (92 kg)
- Patient's BSA: 2.32 m^2
- Settings: V_T = 552 to 736 mL (range of 6–8 mL/kg IBW)
- Normal $\dot{V}_E$ = 4 × 2.32 = 9.28 L/min
- Lung condition assumed to be normal at this time

Possible Initial Settings

- VC-CMV, V_T = 0.6 L; f = 15 breaths/min; flow = 60 L/min using descending ramp
- F_IO_2 = 1.0; PEEP = 3 cm H_2O

After 30 minutes on the initial settings, ABGs are pH = 7.43; P_aCO_2 = 36 mm Hg; P_aO_2 = 450 mm Hg; and HCO_3- = 24 mEq/L. ICP = 18 mm Hg. F_IO_2 is reduced to 0.5, and the patient is maintained on these settings until reevaluation in 2 hours. Additional changes should be directed toward reducing ICP.

ACUTE RESPIRATORY DISTRESS SYNDROME

ARDS is recognized as one of the most complex pulmonary disorders to manage. Mortality rates have been reported to range from 30% to 70%.[34-39] Box 7.9 lists the diagnostic criteria for ARDS, and Box 7.10 lists some precipitating factors leading to this disorder. The characteristic pathophysiological findings associated with ARDS include hypoxemia, increased pulmonary vascular permeability, bilateral radiographic opacities, venous admixture, increased lung weight, and decreased lung compliance. ARDS has been described as having two phases: an early phase (first 7–10 days), which is characterized by increased vascular permeability, lung water, and lung protein; and a later phase (after 10 days), which is accompanied by extensive lung fibrosis.[52-54] Management of ARDS inevitably includes mechanical ventilatory support.[55]

BOX 7.9 Diagnostic Criteria for Acute Respiratory Distress Syndrome[39]

- History of precipitating condition (see Box 7.10) that occurs within 1 week of a known clinical insult
- Diffuse bilateral alveolar infiltrates on chest radiograph (or computed tomography scan) not fully explained by effusions, lobar/lung collapse, or nodules
- Pulmonary edema not fully explained by cardiac failure or fluid overload. Objective assessment to verify if no risk factor is present
- Reduced lung compliance (C_L) (<40 mL/cm H_2O)
- Refractory hypoxemia (reduced partial pressure of arterial oxygen [P_aO_2]/fractional inspired oxygen concentration [F_IO_2])
- Mild ≤200 mm Hg P_aO_2/ F_IO_2 ≤300 mm Hg with 5 cm H_2O PEEP
- Moderate <100 mm Hg ≤200 mm Hg with 5 cm H_2O PEEP
- Severe ≤100 mm Hg with 5 cm H_2O PEEP

BOX 7.10 Examples of Conditions Associated With Development of Acute Respiratory Distress Syndrome

- Sepsis
- Aspiration of gastric contents
- Thoracic and nonthoracic trauma
- Heroin or other drug overdose
- Massive blood transfusions
- Fat emboli
- Smoke inhalation or chemically induced lung injury
- Pulmonary vasculitis
- Burns
- Pancreatitis
- Near-drowning
- Interstitial viral pneumonitis
- Disseminated intravascular coagulation
- O_2 toxicity
- Prolonged cardiopulmonary bypass

Guidelines for Patients With ARDS

For patients with ARDS, a V_T of 6 to 8 mL/kg with a respiratory rate of 15 to 25 breaths/min is indicated. Use of lower than normal V_Ts (V_T = 4–6 mL/kg) may be necessary to maintain the P_{plat} below 30 cm H_2O. This protective lung strategy has been shown to reduce the risk for ventilator-induced lung injury and improve outcomes for ARDS patients. As discussed in earlier chapters, it is important to remember that the use of high respiratory rates and low V_T may not provide sufficient time for exhalation and ultimately lead to air being trapped in the lungs during exhalation (auto-PEEP).

The following guidelines are suggested for ventilation in patients with ARDS[3-5,34-36,43,52-55]:

- Choose a mode capable of supporting oxygenation and ventilation, such as PC-CMV or VC-CMV.
- Maintain S_aO_2 at 88% to 90% or greater. Start at 100% O_2. To support oxygenation, use $PEEP_E$ at a level that prevents alveolar collapse but minimizes overdistention to prevent lung damage. $PEEP_E$ may allow reduction of F_IO_2 to safe levels.
- When oxygenation is inadequate, sedate, paralyze, and consider prone positioning. Cardiac output and hemoglobin levels should be optimized. High $PEEP_E$ levels greater than 15 cm H_2O may be required in ARDS.
- Keep P_{plat} below 30 cm H_2O by lowering V_T to 4 to 6 mL/kg, if necessary. Allow P_aCO_2 to rise above normal (permissive hypercapnia) if necessary, unless there is a risk for increased ICP or contraindications exist that demand a normal P_aCO_2 or pH. Rapid rises in P_aCO_2 should be avoided.

There is no evidence to date that PC-CMV is superior to VC-CMV, or vice versa. The selection of one mode over the other may depend on clinician comfort levels. If VC-CMV is selected, the clinician should use the descending flow waveform to help ensure early delivery of V_T and provide a higher mean airway pressure (P_{aw}) than a constant flow pattern, which may benefit oxygenation and minimizes the difference between PIP and P_{plat}.

During the acute phase of the disease, patients typically require high levels of ventilatory support, although full support is usually not necessary. These levels can be attained with either CMV or IMV + PSV. Adequate ventilation can generally be provided with V_T in the range of 4 to 6 mL/kg while P_{plat} is maintained at below 30 cm H_2O with rates of 15 to 25 breaths/min. Use flow greater than 60 L/min for volume-controlled ventilation. During pressure-controlled ventilation, use a T_I that is long enough to enhance oxygenation but short enough to allow adequate T_E to avoid auto-PEEP (e.g., T_I <1 second). Because time constants are short for many lung units (decreased compliance), this is usually not difficult even for I/E ratios of 1:1.5 or higher (e.g., 1:1 or 2:1).

$PEEP_E$ is required for the management of ARDS to prevent the opening and closing of alveoli during each breath. This opening and closing can cause lung injury from the shear stress (frictional forces) between alveoli that have different time constants and may also result in surfactant being "milked" from the alveoli (Fig. 7.4).[54,55] During the early phase of ARDS, it is important to keep $PEEP_E$ high enough at least to exceed the inflection point on a slow or static pressure-volume curve (see Chapter 13).[55,56] It is generally accepted by clinicians that the deflation limb of a slow pressure-volume loop best approximates the end-expiratory pressure range required to prevent alveolar collapse.[57] Maintaining $PEEP_E$ above this pressure range helps prevent opening and closing of small airways and alveoli (i.e., this is often referred to as the *open lung approach* to ventilator management).[55-59] Even if a ventilator does not have a graphics package, this curve can be graphed by hand. $PEEP_E$ may also be beneficial in later stages of ARDS to maintain oxygenation and reduce the F_IO_2 levels (<0.5). More information about the management of ARDS is presented in Chapter 13.

Acceptable endpoints for the management of ARDS based on ABGs are P_aCO_2 = 40 to 80 mm Hg; pH = 7.20 to 7.40; P_aO_2 = 60 to 100 mm Hg. Note that these values may vary across institutions. Some physicians prefer to use tris-hydroxymethyl-aminomethane or sodium bicarbonate when pH drops below 7.20.[42,59]

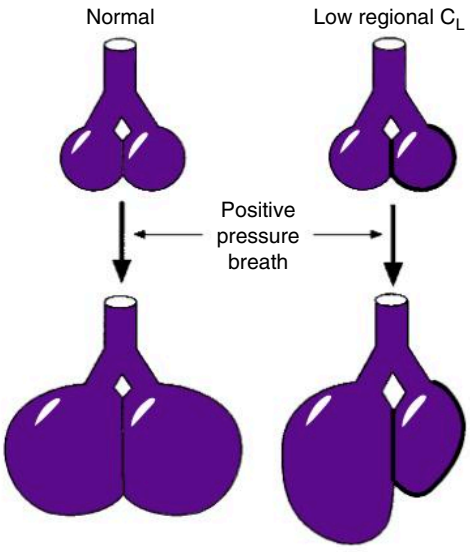

Fig. 7.4 The volume from a positive pressure breath distributes homogeneously throughout the lung with normal lung compliance (C_L) *(left panel)*. In a lung with low regional C_L, the volume from a positive pressure breath distributes preferentially to the regions with more normal C_L *(right panel)*. Thus a tidal volume (V_T) of normal size in a lung with regions of low C_L can overdistend the healthier regions. This may create shear stress (frictional forces) between adjacent lung units. (Redrawn from MacIntyre NR: Minimizing alveolar stretch injury during mechanical ventilation, *Respir Care* 41:318—326, 1996.)

Clinical Scenario: Patient With Acute Respiratory Distress Syndrome

A 60-year-old man sustained multiple lacerations from a motor vehicle crash. Admission to the ED for evaluation revealed a fractured left femur, a deep laceration of the right arm, an open pneumothorax on the right side of the chest, and abdominal bruising. There was evidence of injury to the head or neck. The patient was taken to surgery for repair of internal injuries; a chest tube with pleural drainage was inserted for the pneumothorax.

The patient developed a fever of 39.5° C and severe refractory hypoxemia 4 days after surgery. A chest radiograph showed resolution of the pneumothorax and the presence of bilateral fluffy infiltrates. ABGs on a nonrebreathing mask at the time were pH = 7.29; P_aCO_2 = 51 mm Hg; P_aO_2 = 76 mm Hg; HCO_3- = 24.8 mEq/L. Vital signs were blood pressure = 148/90 mm Hg; heart rate = 152 beats/min; f = 40 to 42 breaths/min and labored. The patient was restless and anxious. Mask CPAP was initiated with F_IO_2 = 1.0 and greater than 10 cm H_2O. The face mask was not well tolerated. The patient, who was 6 ft, 2 in (72 in) and weighed 258 lb (117 kg), was sedated, paralyzed, orally intubated, and placed on ventilatory support (Case Study 7.2). (NOTE: The progress of this patient is continued in Chapter 13.)

Case Study 7.2

Key Questions for Acute Respiratory Distress Syndrome (ARDS) Patient

1. What were the indications for ventilation of this patient?
2. What clinical information suggests this patient may have developed ARDS?
3. What would be appropriate initial ventilator settings for this patient?

ACUTE CARDIOGENIC PULMONARY EDEMA AND CONGESTIVE HEART FAILURE

Cardiovascular disease is the most common cause of death in the United States (Centers for Disease Control and Prevention). It is not surprising that many patients with cardiovascular problems seek medical help in both EDs and urgent care centers. These problems can take the form of shortness of breath with or without accompanying chest pain.

Patients with congestive heart failure (CHF) can rapidly develop acute pulmonary edema. Box 7.11 lists the most common causes of cardiogenic pulmonary edema.

Much of the treatment of acute heart failure is based on medical management. For example, diuretics are given to reduce vascular fluid load, positive inotropic agents are given to improve cardiac contractility, and vasodilators can improve myocardial oxygenation and reduce preload and afterload. Many patients can be successfully managed with drug therapy and do not require mechanical ventilatory support. However, mechanical ventilation may be indicated when severe heart failure leads to increased myocardial work, increased WOB, and hypoxemia. In patients with left ventricular failure the use of positive pressure, particularly PEEP (Box 7.12, 1 through 4), can effectively reduce the size of the heart and therefore reduce venous return and reduce preload to left ventricles.[3,37] Reducing the size of an overdistended left ventricle can improve the relationship of left ventricular length to tension and allow for an increase in stroke volume. PEEP increases intrathoracic pressures and reduces venous return, thus reducing preload to the heart.

Guidelines for Patients With Congestive Heart Failure

The following guidelines are recommended for mechanical ventilation in patients with acute cardiogenic pulmonary edema and CHF[3-5,41-43]:

BOX 7.11 Common Causes of Acute Pulmonary Edema

- Acute myocardial infarction
- Hypertension
- Rapid heart rates with inadequate filling time
- Valvular heart disease
- Fluid overload

- Select a mode of ventilation that reduces WOB. This may be as simple as noninvasive mask CPAP. NIV by mask CPAP may improve oxygenation, reduce P_aCO_2, reduce the WOB, and reduce myocardial work. NIV in patients with CHF may allow sufficient time for pharmacological treatment to become effective.
- When life-threatening hypoxemia occurs with severe CHF, PEEP or positive pressure ventilation may have beneficial effects on myocardial function and improve oxygenation.
- Careful evaluation of the effects of positive pressure ventilation on hemodynamics is essential. This may include the use of a pulmonary artery catheter in severe cases, particularly if $PEEP_E$ greater than 10 to 15 cm H_2O is used. However, the use of pulmonary catheters carries a risk for increased mortality and morbidity and is controversial (see Chapter 11 for more details about hemodynamic monitoring).
- The use of VC-CMV or PC-CMV is recommended to minimize spontaneous breathing, which may divert increased blood flow and O_2 consumption to the respiratory muscles.
- V_T range is moderate from 6 to 8 mL/kg: set f from 10 or more breaths/min and peak flows 60 L/min or greater using either descending or constant waveforms. T_I range is 1 to 1.5 seconds.
- Set a PEEP of 5 to 10 cm H_2O to support the cardiac function.
- Start F_IO_2 at 1.0 and titrate quickly with S_pO_2 to maintain S_pO_2 greater than 90% to 92%.
- Monitor S_pO_2, ABGs, urine output, electrolytes, and systemic hemodynamic status.

BOX 7.12 Potential Effects of PEEP in Left Ventricular Dysfunction

1. Increased mean airway pressure (P_{aw}) and intrathoracic pressure lead to reduced venous return, which can reduce preload to a failing heart, improving its function.
2. Increased functional residual capacity from PEEP leads to increased pulmonary vascular resistance and increased afterload to the right heart and decreased left heart filling. Increased right heart pressures with the increased afterload may shift the interventricular septum to the left. This does not seem to alter right ventricular contractility until values for pulmonary artery pressure are critical.
3. With the left shift of the interventricular septum, the left ventricular volume is reduced. This may reduce the load it must pump. However, it may also affect the compliance of the left ventricle and either increase or decrease left heart function (the response varies).
4. The mechanical compression of the heart and aorta by the pleural pressure surrounding them can also alter ventricular function. The vascular pressure in the heart and thoracic aorta is transiently increased relative to the extrathoracic aorta (i.e., left ventricular afterload decreases). This response is not always consistent, and cardiac tamponade from PEEP can negatively alter myocardial compliance as well.
5. If ventilator modes increase work of breathing, this increases O_2 demand and can lead to increased myocardial ischemia and a reduction in left ventricular compliance.

Clinical Scenario: Patient With Congestive Heart Failure

A 63-year-old man who is complaining of severe shortness of breath is brought by ambulance to the ED. He is 5 ft, 11 in (71 in) and weighs 175 lb (79.5 kg). His vital signs are blood pressure = 175/115 mm Hg, heart rate = 140 beats/min and the rhythm is irregular, f = 22 to 24 breaths/min, and normal temperature. His lips are cyanotic, his neck veins are distended, and both of his ankles show evidence of pitting edema. Breath sounds reveal bilateral basilar crackles and wheezes. He has a productive cough with small amounts of pink, frothy secretions. He is anxious and refuses to lie down on the gurney, saying, "I get too short of breath when I lie down."

A chest radiograph shows cardiomegaly and dense, fluffy opacities in the lower lung fields. The electrocardiogram reveals atrial fibrillation with a ventricular rate of 138 to 140 beats/min and occasional premature ventricular contractions. The respiratory therapist places a pulse oximeter sensor on the patient's left index finger and notices that the patient's hand is cold. The respiratory therapist is unable to obtain an accurate pulse oximeter reading (Case Study 7.3). After placing the sensor on the right index finger and rubbing the hand to warm it, an S_pO_2 reading of 87% is obtained.

The patient is started on a nasal cannula at 2 L/min and given intravenous furosemide, dobutamine, and digitalis. ABGs obtained 1 hour later are pH = 7.16; P_aCO_2 = 79 mm Hg; P_aO_2 = 33 mm Hg; and HCO_3- = 28 mEq/L on 2 L/min by nasal cannula. The patient's urine output was 580 mL in the past hour, and he remained cyanotic. The 2 L/min nasal cannula was not adequate. He is slow to respond to verbal commands. The following information provides an alternative therapeutic approach using NIV.

Alternative Solution to Patient Treatment: CHF

Noninvasive ventilation is started for this patient using a full-face mask and bilevel PAP with IPAP at 9 cm H_2O, EPAP at 3 cm H_2O, and F_IO_2 of approximately 0.5. The patient's spontaneous respiratory rate on these settings is 25 breaths/min, and the S_pO_2 is now 88%.

To reduce f and S_pO_2, the IPAP and EPAP are increased. After several adjustments, the final values for adequate ventilation are IPAP = 15 cm H_2O; EPAP = 5 cm H_2O; approximate F_IO_2 = 0.6; f = 16 breaths/min; and V_T = 760 mL. S_pO_2 = 95%.

The patient's condition improves with treatment. Urine output is 850 mL over a 2-hour period. Breath sounds reveal a moderate amount of crackles in the lung bases. The patient's color improves and he is alert, responsive, and cooperative. The pressure support levels are gradually reduced. The patient is alternately tested with a 50% O_2 mask and returned to the noninvasive ventilator until he is stable on the 50% mask. ABGs on an F_IO_2 = 0.5 are pH = 7.38; P_aCO_2 = 45 mm Hg; P_aO_2 = 73 mm Hg; and HCO_3- = 26 mEq/L. The patient is monitored over the next 24 hours, stabilized on medication, and discharged into the care of his wife.

Although NIV was successful in this individual, it is important to recognize that it is not always successful. Some patients with decompensated heart failure will temporarily improve with NIV but then worsen and may even go into cardiac arrest. Some clinicians prefer to intubate and provide invasive ventilation rather than NIV in this patient population because invasive ventilation provides more controlled conditions.

Case Study 7.3

Troubleshooting: The Pulse Oximeter

Why was the therapist unable to get an initial reading from the pulse oximeter? What would you suggest to alleviate this situation?

SUMMARY

- Numerous issues must be considered before connecting a patient to a mechanical ventilator. These include selecting appropriate ventilator settings for F_IO_2, sensitivity, sigh breaths, alarms, and monitors, as well as concerns regarding humidification of inspired gases.
- Once the patient is connected to the ventilator, the clinician should perform a careful assessment of the patient's response to these initial parameters.
- Titrating the F_IO_2 using pulse oximetry and ABG findings can minimize the risk for administering too much O_2.
- Ventilator sensitivity is normally set so that patients can easily flow-trigger or pressure-trigger a breath.
- It can be particularly difficult to adjust the ventilator sensitivity so that it senses a patient's effort when auto-PEEP is present.
- Humidity can be provided by a variety of humidification systems. Devices in this category include the following types of humidifiers: pass-over, vapor phase, wick, and active heat and moisture exchangers.
- Audible and visible alarm systems are designed to alert the operator of potential dangers related to the patient-ventilator interaction.
- Initial ventilator setting should be based on the patient's condition. Table 7.1 provides a summary of initial ventilator settings for patients commonly encountered in the clinical setting.
- Mechanical breaths of V_T 6 to 8 mL/kg IBW are usually effective, but lower V_Ts may be required for patients with ARDS to maintain P_{plat} below 30 cm H_2O. Low levels of PEEP (3—5 cm H_2O) can reduce atelectasis formation.

TABLE 7.1 Initial Ventilator Settings Based on Pulmonary Disorder[a]

Lung Disease	Mode	V_T (mL/kg IBW)	Rate (breaths/min)	Flow (L/min)	Flow Waveform	T_I (s)	PEEP (cm H_2O)	F_IO_2
Normal lungs	VC- or PC-CMV	6–8	10–15	60	Descending or constant	1	≤5	≤0.5
COPD[b]	VC- or PC-CMV	6–8	8–12	>60 (80–100)	Descending or constant	0.6–1.2	≥5 or 50% of intrinsic PEEP	<0.5
Neuromuscular disorder	VC-CMV	6–8	8–12	≥60	Descending or constant	1	5	0.21
Asthma	VC- or PC-CMV	6–8	10–14	60–70	Descending	≤1	Only to offset intrinsic PEEP and improve triggering	≥0.5
Closed head injury	PC- or VC-CMV	6–8	15–20	60	Descending or constant	1	0–5 with caution Only in severe hypoxemia	1.0
ARDS	PC- or VC-CMV	4–8	12–35	≥60	Descending or constant	1	5 to >15	1.0
CHF	VC- or PC-CMV	6–8	≥10	≥60	Descending or constant	1–1.5	5–10	1.0

[a]For all disorders it is important that the plateau pressure be maintained lower than 30 cm H_2O.
[b]An initial attempt at bilevel PAP should be tried using NIV with IPAP = 10–12 cm H_2O and EPAP = 2–3 cm H_2O before intubation is considered. An exception would be a critical emergency with these patients.
ARDS, acute respiratory distress syndrome; *CHF,* congestive heart failure; *CMV,* continuous mandatory ventilation; F_IO_2, fractional inspired oxygen concentration; *IBW,* ideal body weight; *PC,* pressure control; *PEEP,* positive end-expiratory pressure; V_C, volume control; V_T, tidal volume.
Sources: Meade MO, Herridge MS: An evidence-based approach to acute respiratory distress syndrome, *Respir Care* 46:1368–1376, 2001; and Slutsky AS, Ranieri M. Ventilator-induced lung injury, *N Engl J Med*. 2013;369:2126–236, 2013.

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

1. A male patient has a BSA of 1.5 m^2; is 5 ft, 8 in; and weighs 175 lb. The patient has a history of lung damage resulting from old tuberculosis scars. He demonstrates a restricted breathing pattern. What ventilator settings would you select for this patient?
   $\dot{V}_E$: _____
   V_T: _____
   f: _____

2. A patient with COPD is on ventilation with a PB 980 ventilator. Ventilator parameters are VC-CMV: flow = 40 L/min with descending ramp flow waveform; V_T = 0.65; F_IO_2 = 0.3. At 2:00 p.m., total f = 10 breaths/min, PIP = 28 cm H_2O, there are no assisted breaths, and the pressure-time curve is normal. At 4:00 p.m., total f = 20 breaths/min, PIP = 37 cm H_2O, the patient is actively assisting and using accessory muscles to breathe, and the pressure-time graphic shows a concave appearance.
   What do you think has caused the changes in the patient's condition? What would you do to correct this situation?

3. An 83-year-old man with COPD is being treated in the ED. His wife, who brought him in, states, "He's been so short of breath and pale and I'm worried." O_2 by a 28% air-entrainment mask is begun. The patient is given an aerosol treatment with albuterol. Despite continued therapy, the patient does not improve and continues to use accessory muscles to breathe. He is diaphoretic and pale, and his temperature is 102° F. The decision is made to begin noninvasive ventilation. A BiPAP unit is set up with initial pressures of inspiratory positive airway pressure (IPAP) = 6 cm H_2O and expiratory positive airway pressure (EPAP) = 2 cm H_2O. These were then adjusted on the basis of pulse oximetry and patient f. With an IPAP/EPAP ratio of 12 cm H_2O to 4 cm H_2O and a measured F_IO_2 of 0.3, the patient has a rate of 25 breaths/min and S_pO_2 of 87%. Vital signs, S_pO_2, and respiratory rate remain fairly stable.
   Two hours later, the patient's respiratory rate has increased to 35 breaths/min. ABGs reveal pH = 7.21; P_aCO_2 = 105 mm Hg; P_aO_2 = 47 mm Hg; and HCO_3- = 40 mEq/L. Repeated adjustments of the IPAP/EPAP ratio fail to improve the patient's condition; the decision is made to intubate him and provide him with volume-targeted ventilation. The patient is 5 ft, 8 in and weighs 148 lb (IBW = 70 kg). BSA = 1.78 m^2. The VC-IMV mode is selected.
   What initial V_T, $\dot{V}_E$, and f would you select?
   After initiating mechanical ventilation, the following values are noted: PIP = 33 cm H_2O; P_{plat} = 25 cm H_2O; transairway pressure (P_{TA}) = 33 – 25 = 8 cm H_2O. The patient is spontaneously breathing an additional 10 breaths/min with a V_T of 200 mL. The decision is made to add pressure support for the spontaneous breaths to overcome the WOB imposed by the artificial airway.
   What is an estimated resistance on this patient, assuming a constant flow of 80 L/min is used for calculation? Where would you set pressure support?

4. A 50-year-old patient is receiving VC-CMV after surgery for a bowel resection. He is in the recovery room. The patient has an IBW of 80 kg and a BSA of 1.8 m^2. This patient's lungs are normal. What initial settings would be appropriate?

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CHAPTER 8

Initial Patient Assessment

OUTLINE

KEY TERMS

- Ascites
- Driving Pressure
- Dynamic characteristic
- Lower inflection point
- Operational verification procedure
- Patient-ventilator system check
- Upper inflection point
- Ventilator flow sheet

LEARNING OBJECTIVES

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

1. Understand the importance of performing an operational verification procedure.
2. State the recommended times when an oxygen analyzer is used to measure the fractional inspired oxygen concentration (F_IO_2) during mechanical ventilation.
3. Identify various pathophysiological conditions that alter a patient's transairway pressure, peak pressure, and plateau pressure.
4. Use pressure-time and flow-time curves obtained during pressure-controlled continuous mandatory ventilation to determine the plateau pressure.
5. Identify a system leak from a volume-time curve.
6. Use physical examination and radiographic data to determine whether pneumonia, acute respiratory distress syndrome, flail chest, pneumothorax, asthma, pleural effusion, or emphysema is present.
7. Determine whether a lung compliance problem or an airway resistance problem is present, using the ventilator flow sheet and time, volume, peak inspiratory pressure, and plateau pressure data.
8. Evaluate a static pressure—volume curve for static compliance and dynamic compliance to determine changes in compliance or resistance.
9. Estimate a patient's alveolar ventilation based on ideal body weight, tidal volume, and respiratory rate.
10. Detect a cuff leak by listening to breath sounds.
11. Recognize inappropriate endotracheal tube cuff pressures and an inappropriate tube size and recommend measures to correct these problems.
12. Evaluate flow sheet information about a patient on pressure control ventilation and recommend methods for determining whether compliance and airway resistance have changed.
13. Explain the technique for measuring endotracheal tube cuff pressure using a manometer, syringe, and three-way stopcock.
14. Describe two methods that can be used to remedy a cut pilot tube (pilot balloon line) without changing the endotracheal tube.

Assessing a patient's oxygenation status, respiratory rate, breathing pattern, use of accessory muscles, chest movement, and breath sounds, along with estimates of work of breathing (WOB) and evaluation of the patient's level of consciousness, can provide valuable information about a patient's physiological status. These observations, along with information derived from ventilator displays and hemodynamic monitoring, are among the first assessments the clinician records for a patient who is undergoing mechanical ventilation.[1]

This chapter reviews assessment and documentation of patient-ventilator interactions after a patient has been placed on a mechanical ventilator. The first step in this process involves verification of the physician's orders for initiating mechanical ventilator support (Box 8.1). Once the physician's orders have been verified, the respiratory therapist ensures that the designated ventilator has passed an **operational verification procedure** (OVP). The OVP process is typically described in the respiratory therapy department's policies and procedures manual.

It is important that the respiratory therapy department maintains records showing the OVP history for each ventilator. In addition, a label or form should be attached to each ventilator showing when the OVP was performed, by whom, and whether the ventilator passed the multiple-part test. Newer microprocessor-controlled ventilators are designed to perform a series of automated self-tests once the operator initiates the self-test process. This self-test record may be part of the OVP.

The equipment evaluation process should also involve checking the integrity of the ventilator circuit and humidifier system and ensuring that related equipment has been correctly attached and tested to ensure that the system is free of leaks (Box 8.2).

DOCUMENTATION OF THE PATIENT-VENTILATOR SYSTEM

In addition to documentation of the OVP, patient information and ventilator settings should be documented regularly when a patient is receiving ventilatory support. These data can be recorded on a computer software program with specific entry fields or kept as a paper record. Regardless of the form it takes, the document often is called a **ventilator flow sheet.**

The frequency of patient-ventilator system checks depends on the institution's policy. They are generally performed every 1 to 4 hours. In addition to this schedule, patient-ventilator system checks are performed as follows:

- Before an arterial blood gas (ABG) sample is drawn
- When the physician has entered new orders
- Before hemodynamic data or bedside pulmonary function data are measured
- After a ventilator change has been made
- If an acute change occurs in the patient's condition (such changes should be documented as soon as possible after the event)
- After a patient returns from testing (e.g., x-ray or magnetic resonance imaging [MRI])
- Whenever the ventilator's performance is questionable

It is important to recognize that **patient-ventilator system checks** represent a documented evaluation of the ventilator's function and the patient's response to ventilatory support. The following points regarding patient-ventilator system checks should be emphasized:

- Data relevant to the patient-ventilator system check are recorded on the appropriate hospital form and are part of the patient's medical record.
- The patient-ventilator system check includes observations of ventilator settings at the time of the check.
- The record should include the physician's order for mechanical ventilator settings.
- The patient-ventilator system check includes a brief narrative of the clinical observations of the patient's response to mechanical ventilation at the time of the check.

Fig. 8.1 shows a typical ventilator flow sheet used to record patient-ventilator system check data. The top of the form contains

BOX 8.1 Physician's Orders for Mechanical Ventilation

The orders written by the physician for mechanical ventilation settings vary among institutions. In some instances the physician's orders may be specific, with little flexibility for respiratory therapist involvement. More commonly, the physician orders simply request a particular protocol for mechanical ventilation, which is then followed by the respiratory therapist, nurse, and other staff members involved with the care of the patient.[2]

The orders or protocol should include at least one (and preferably both) of the following:

- Desired range for the arterial CO_2 partial pressure (P_aCO_2) or end-tidal carbon dioxide partial pressure ($P_{ET}CO_2$), and/or for the arterial oxygen partial pressure (P_aO_2), arterial oxygen saturation (S_aO_2), oxygen saturation as measured by pulse oximetry (S_pO_2), or transcutaneous oxygen partial pressure ($P_{tc}O_2$).
- Ventilator variables to be initiated or manipulated to achieve the desired arterial blood gases (e.g., mode, tidal volume [V_T], respiratory rate [f], set pressure, and fractional inspired oxygen [F_IO_2]) while protecting the lung.

BOX 8.2 Simple Verification of Ventilator Operation

A simple ventilator check should be performed:

- Before connecting a patient to a ventilator for the first time.
- Before reconnecting the patient to a ventilator if the circuit has been changed or disassembled for any reason.

The operational verification procedure should also include checking the system for leaks before the patient is connected to the ventilator. To check for leaks, the operator should:

- Set the tidal volume (V_T) at 500 mL, the gas flow low (e.g., 20 L/min), the maximum pressure limit high (e.g., 100 −120 cm H_2O), and an inspiratory pause of 1 to 2 seconds.
- Occlude the Y-connector, cycle the ventilator, and observe the airway pressure rise and pause on the pressure manometer; if no leak is present, the circuit will hold the pressure steady.
- Change the ventilator settings to those appropriate for the patient before connecting the patient to the ventilator.
- Newer microprocessor-controlled ventilators automatically perform a test to check for leaks in the patient-ventilator circuit. This test can be performed at any time, but the patient must be disconnected from the ventilator to perform the test.

Patient Name _____ Medical Record Number_____ Date of Birth _____ Age _____

Physician _____ Diagnosis _____ Vent. Start Date _____ Vent Day_____

Height _____ Weight _____ IBW ____ BSA____ ET size_____ Position (teeth/lips/nose) _____

Original Physician Order _____; Circuit Change Due Date _____

	Date	____	____	____
	Time			
	Therapist Initials			
	MODE*			
V	Auto-Wean Mode (on/off)			
O	V_{Tset}/V_{Texh}			
L	V_T spont			
U	Machine rate/Total rate			
M	I/E ratio (or Set T_I%)(or T_{HI}/T_{LO})			
E	Minute Ventilation			
	Increase V_{Dmech} (mL)			
P	P_{peak}/P_{plat}			
R	Compliance (V_T/PIP-$PEEP_{TOT}$)			
E	R_{aw} [(PIP-Pplat)/flow(L/s)]			
S	IPAP/EPAP (P_{HI}/P_{LO})			
S	Mean Airway Pressure			
U	Set Pressure (PCV or PS)			
R	Set PEEP/CPAP			
E	Auto-PEEP			
	Sensitivity (P or Flow setting)			
M	F_IO_2 (set/analyzed)			
I	Flow rate			
S	Flow waveform			
C	Insp. Rise Setting			
	Inspir Flow cycle			
	Automatic Tube Comp. Set (yes/no)			
	Air Temperature			
A	Apnea Parameters Set (yes/no)			
L	Press. Limit (high/low)			
A	Low V_T			
R	V_E (high/low)			
M	High Rate			
	Low PEEP			
A	Suctioned (yes/no)			
I	Secretion color			

Fig. 8.1 Example of a ventilator flow sheet.

R	Secretion consistency			
W	Secretion Amt. (small/mod./lg)			
A	ET Repositioned/Taped (yes/no)			
Y	Cuff (Press/Vol.)/Tube position			
	MLT or MOV			
	Aerosol Therapy (MDI or Neb)			
	Medication/Dose			
	pH/$PaCO_2$			
A	$P_{ET}CO_2$			
B	P_aO_2			
G	S_pO_2			
	Hb			
	HCO_3^-			
	B.E.			
	P_aO_2/F_IO_2 or P_aO_2/P_AO_2			
	C_aO_2/C_aO_2-$C\bar{v}O_2$			
H	Pulse			
E	Blood Pressure			
M	CVP			
O	PAP (sys/dys)			
	PAWP			
	C.O./C.I. (C.O./BSA)			
	SVR			
	PVR			
S	Spontaneous rate			
P	Spontaneous V_T			
O	RSBI (f/V_T [breaths/min/L])			
N	MIP (NIF)			
T	VC			
	Time of SBT			
	COMMENTS			
M **O** **D** **E** **S**	*VC-CMV (A/C), PC-CMV (PCV), VC-SIMV; PC-SIMV VC-SIMV + PS; PC-SIMV + PSV PRVC; APRV Spontaneous, PSV, VS, CPAP BiLevel PAP			

Fig. 8.1, cont'd

basic patient information, including the patient's name and anthropometric data (e.g., age, weight, height, ideal body weight [IBW], body surface area), medical record identification number, patient's diagnosis, name of the attending physician along with the physician's orders, date of intubation, ventilator start date, and ventilator day (number of days on the ventilator).

The form will typically include spaces for entering current information about the patient and measurements of ventilator parameters. These may include the following:

- Date
- Time
- Mode of ventilation

- Minute ventilation ($\dot{V}_E$)
- Respiratory rate (f)
- Tidal volume (V_T)
- Peak inspiratory pressure (PIP)
- Plateau pressure (P_{plat})
- Static compliance (C_s)
- Airway resistance (R_{aw})
- Fractional inspired oxygen (F_IO_2)
- Temperatures of inspired gases
- Inspiratory-to-expiratory ratio
- Continuous positive airway pressure (CPAP) or positive end-expiratory pressure (PEEP)
- Inspiratory and end-expiratory positive airway pressures
- Arterial blood gases (ABGs)
- Alveolar-to-arterial partial pressure of oxygen ($P_{[A\text{-}a]}O_2$) or ratio of arterial oxygen partial pressure to fractional inspired oxygen (P_aO_2/F_IO_2)
- Vital capacity (VC)
- Maximum inspiratory pressure
- Vital signs
- Alarm settings

Volumes, pressures, temperature, vital signs, and F_IO_2 are measured during each patient-ventilator system check. Most intensive care unit (ICU) ventilators have O_2 analyzers that provide continuous monitoring of F_IO_2. In cases in which continuous F_IO_2 measurements are not available on a particular ventilator, intermittent measurements of F_IO_2 are usually sufficient for adult patients. F_IO_2 should be continuously monitored, however, for infants receiving mechanical ventilation. Alarms should be regularly checked to ensure they have been set appropriately. ABGs, shunt fraction, $P_{(A\text{-}a)}O_2$, and P_aO_2/F_IO_2 should be determined when the patient's condition or the ventilator settings change significantly.

Regular, accurate documentation of patient-ventilator system checks are essential for the effective use of mechanical ventilation and for maintaining patient safety.[2-4] Case Study 8.1 provides a clinical scenario illustrating the importance of maintaining accurate patient-ventilator records.

Case Study 8.1

The Importance of Documentation

A 38-year-old woman is intubated for respiratory failure secondary to severe pneumonia. After 24 hours her status improves. The endotracheal tube is kept in place to allow suctioning, because she has large amounts of secretions. On the third day after intubation, her respiratory status declines. She has a cardiac arrest and is resuscitated but suffers brain injury as a result. She dies several weeks later.

The family hires an attorney. At issue is the fact that in the medical record, the respiratory therapist's notes with the ventilator flow sheet indicate that the patient had been suctioned about every 2 hours for large amounts of thick, yellow secretions. However, during the 8 hours before the arrest, nowhere did the notes state that the patient had been suctioned. The therapist states that he had suctioned the patient but had not recorded it in the chart. Was the therapist negligent and did his actions lead to the wrongful death of the patient?

***Key Point* 8.1** Positive pressure ventilation can reduce venous return to the heart, cardiac output, and blood pressure. (See Chapter 16 for more information on the cardiovascular effects of mechanical ventilation.)

THE FIRST 30 MINUTES

Immediately after the patient is connected to a mechanical ventilator, the clinician should perform auscultation of the patient's chest to confirm adequate volume delivery and proper placement of the endotracheal tube (ET). The patient's vital signs are checked, making particular note of heart rate and blood pressure, because mechanical ventilation may affect these parameters (Key Point 8.1). The alarms (e.g., apnea, low pressure, low V_T, and high pressure limit) are activated. An arterial blood sample is obtained about 15 minutes after mechanical ventilation is initiated for evaluation of the effectiveness of ventilation and oxygenation.[5,6] If not already done, a chest radiograph is obtained to confirm proper placement of the ET. Box 8.3 lists other clinical laboratory tests a physician might order to assess the patient's status when mechanical ventilation is initiated.[3]

Once the patient assessment shows the individual is stable, the respiratory therapist then performs the first ventilator check.

Mode

The mode of ventilation is recorded in the appropriate space on the ventilator flow sheet. It may be recorded as follows:

- Volume-controlled continuous mandatory ventilation (VC-CMV)
- Pressure-controlled continuous mandatory ventilation (PC-CMV)
- Intermittent mandatory ventilation (IMV), using either volume-controlled ventilation (VC-IMV) or pressure-controlled ventilation (PC-IMV), with or without pressure support ventilation (PSV)
- Pressure-regulated volume control (PRVC)*
- Airway pressure release ventilation (APRV)
- PSV, volume support (VS), CPAP, unsupported spontaneous ventilation (these are spontaneous modes)
- Bilevel positive airway pressure (bilevel PAP; noninvasive positive pressure ventilation [NIV])

BOX 8.3 Clinical Laboratory Tests for Initial Assessment

The following clinical laboratory tests may be included in the initial evaluation of the patient:

- Complete blood count
- Blood chemistries (glucose, sodium, potassium, chloride, CO_2, blood urea nitrogen, creatinine, phosphate, magnesium)
- Prothrombin time, partial thromboplastin time, international normalized ratio (PT/PTT/INR), and platelet count
- Blood, sputum, and urine cultures

*Other names associated with this mode include *AutoFlow* (Dräger V500) and *VC+* (Medtronics Puritan Bennett 840 and 980 ventilators).

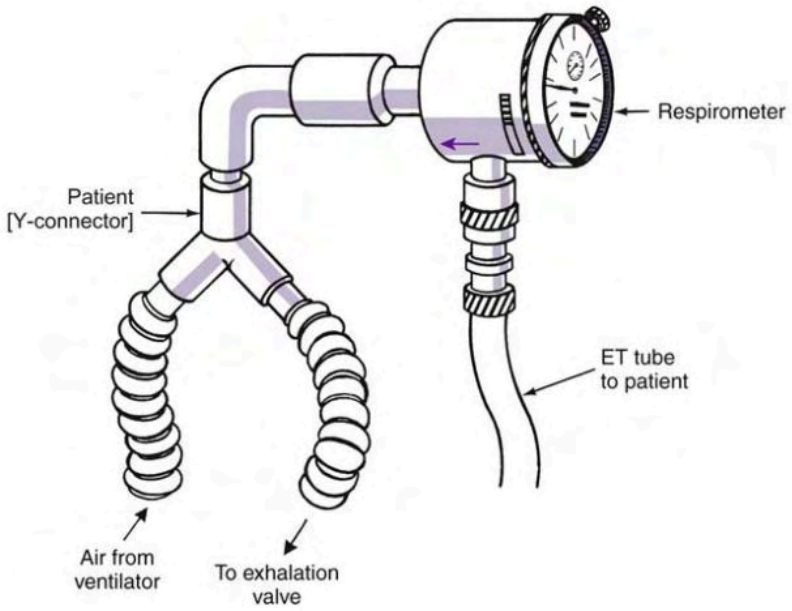

Fig. 8.2 Measurement of tidal volume (VT) at the endotracheal tube (ET). The respirometer is attached to the ET so that the patient's actual exhaled air can be measured. The respirometer can also be attached at the exhalation valve, but those readings would include compressible volume from the ventilator circuit in addition to volume from the patient's lungs.

Sensitivity

If a patient-triggered mode is used (i.e., inspiration is initiated by patient effort), the pressure or flow required to trigger the ventilation should be checked; no more than −1 or −2 cm H_2O should be required. If the ventilator is flow triggered, the sensitivity should be set so that the ventilator will trigger at a flow change of 2 to 3 L/min. The ventilator should be checked for autotriggering, and the patient's ability to trigger a breath should be assessed. Adjustments are made as needed.

As discussed previously, when auto-PEEP is present, the patient has more difficulty triggering breaths. The presence of auto-PEEP should be suspected if the patient is using his accessory muscles of inspiration or demonstrates labored breathing. Ventilator graphics that show failure of the expiratory flow to return to zero before the next breath are also an indicator of auto-PEEP (see Chapter 9).[7]

If auto-PEEP is present, a number of strategies can be used to reduce its effects, including increasing the flow (reducing the inspiratory time [T_I]), reducing V_T, or reducing the rate [i.e., reducing $\dot{V}_E$]), suctioning the patient, or changing modes to allow for more spontaneous breaths. It is important to recognize that it may not always be possible to eliminate auto-PEEP, particularly in patients with increased flow resistance and airway closure. The addition of extrinsic PEEP ($PEEP_E$) in these cases may make triggering easier (see Fig. 7.1). $PEEP_E$ is increased progressively during VC-CMV until the patient's use of accessory muscles diminishes or until PIP and P_{plat} begin to rise. (Additional information about treatment of auto-PEEP can be found in Chapter 17.)

Tidal Volume, Rate, and Minute Ventilation

V_T, f, and $\dot{V}_E$ are typically displayed digitally on the front panel of the ventilator in the data display window. Most ventilators display the set V_T (V_{Tset}) and the exhaled V_T (V_{Texh}). Newer microprocessor-controlled ventilators provide excellent, reliable flow and pressure monitoring. If this information is not available, V_T can be measured using a handheld bedside pulmonary function device or other volume-measuring device (e.g., respirometer) and a watch or clock with a sweep second hand. Although this technique is generally used only with older ventilators, it can also be used to verify digital readouts if a question arises about the machine's reliability (Fig. 8.2 and Box 8.4).

BOX 8.4 Respirometer Technique for Measuring Tidal Volume (VT) and Minute Ventilation (VE)

Modern microprocessor-controlled ventilators provide digital displays for the clinician to monitor a patient's tidal volume and minute ventilation. Before the introduction of these devices, clinicians typically relied on handheld respirometers to measure these variables. The procedure for measuring V_T and $\dot{V}_E$ with a respirometer is relatively easy to accomplish.

- The respirometer is connected directly to the patient's endotracheal tube and Y-connector of the ventilator circuit (see Fig. 8.2). This allows easy measurement of the V_T that does not have to be corrected for compressible volume from the ventilator circuit. (NOTE: In cases in which the V_T was measured at the expiratory port, the compressible volume [volume lost to C_T] must be subtracted from the V_T reading on the respirometer.)
- Gas exhaled from the lungs is measured for 1 minute, and the f is simultaneously counted. $\dot{V}_E$ can be calculated ($\dot{V}_E = V_T \times f$) or measured directly. If the patient is receiving intermittent mandatory ventilation (IMV), the total $\dot{V}_E$ is measured. Mandatory V_T and f can be measured separately, and mandatory $\dot{V}_E$ can be subtracted from the total $\dot{V}_E$ to determine a patient's spontaneous $\dot{V}_E$.

Correcting Tubing Compliance

Accurate reporting of volumes requires correction for volume loss within the patient circuit because of the effects of tubing compliance (also called *compressible volume*). As discussed in Chapter 6, tubing compliance (C_T) for most ventilator circuits ranges from about 1.5 to 2.5 mL/cm H_2O.

Most microprocessor-controlled ventilators (e.g., Medtronics Puritan Bennett 840 [Medtronics Minimally Invasive Therapies], Servo-i [Getinge, Göteborg, Sweden]) do not require calculation of tubing compliance because these machines automatically compensate for this factor. As discussed previously, ventilators that perform this function typically increase the delivered volume so that the set volume is the amount provided to the patient (i.e., the digital readout indicates the V_T actually delivered to the patient's airway). With older ventilators, the operator can set the value for the circuit's C_T and the ventilator will add volume to the V_{Tset} to compensate for volume loss because of tubing compliance.

Alveolar Ventilation

Monitoring of alveolar ventilation ($\dot{V}_A$) has declined in popularity in recent years because many acute care facilities do not include this variable on the ventilator flow sheet. Unfortunately, its importance is often overlooked when using low V_T strategies. In-line heat-moisture exchangers (HMEs), closed suction systems, and other circuit adapters and equipment can add mechanical dead space (V_{Dmech}) to the ventilator circuit and affect the V_D/V_T. Knowledge of the effect of dead space on alveolar volume delivery can be particularly important in infants, children, and smaller adults with acute respiratory distress syndrome (ARDS).*

The following two factors must be considered in determining alveolar ventilation:

1. Anatomical dead space
2. Mechanical dead space

Dead Space

Normal anatomical dead space (V_{Danat}) is about 1 mL/lb IBW. Bypassing the upper airway with an artificial airway reduces V_{Danat} by about half. Using a Y-connector, additional flex tubing between the Y-connector and the ET, or an HME adds mechanical dead space.

Added Mechanical Dead Space

Because HMEs or other adapters attached to the ET (Fig. 8.3) add to V_{Dmech}, the volume of these devices, along with the V_{Danat}, must be subtracted from the V_T to determine actual alveolar ventilation (Box 8.5). For example, if a 150-lb adult has a V_T of 500 mL and the added V_{Dmech} is 100 mL, the alveolar ventilation for each breath would be:

$$VT - V_{Dmech} - V_{Danat} = 500mL - 100 - 150mL = 250mL \text{ (Key Point 8.2)}$$

Key Point 8.2 The volume of mechanical dead space can be easily measured for any device added to a ventilator circuit. The device is simply filled with water and then emptied into a graduated container; the volume measured is the volume of mechanical dead space for the device. (A piece of equipment [i.e., tubing] similar to that being placed on the patient should be used for this type of measurement.)

*Physiological dead space is reviewed in Appendix B.

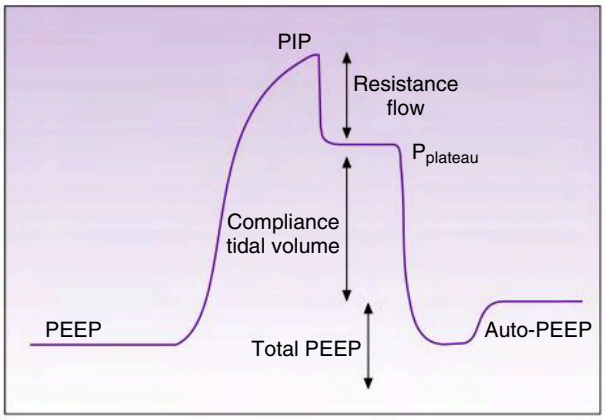

Fig. 8.3 Airway pressure waveform during volume control ventilation. An end-inspiratory breath hold and an end-expiratory breath hold are applied to measure the plateau pleasure and auto-PEEP, respectively. Note the difference between the peak inspiratory pressure (PIP) and plateau pressure (P_{plat}); this is the transairway pressure (P_{TA}), which is produced by the interaction of the set flow and airway resistance. The V_T is the product of the pressure difference between P_{plat} and total PEEP (set PEEP and auto-PEEP) and lung compliance. (From Hess DR, MacIntyre NR, Mishoe SC, et al: *Respiratory care principles and practice,* Philadelphia, PA, 2002, WB Saunders.)

BOX 8.5 Added Mechanical Dead Space

Some patient situations require the addition of a small amount of mechanical dead space. For example, in Fig. 7.3 a small circuit has been added at the Y-connector to allow for intermittent use of a metered-dose inhaler (MDI) without removing the heat and heat-moisture exchanger (HME) or disconnecting the circuit.

Excessive turbulence at the upper airway and Y-connector can sometimes produce a pressure spike at the beginning of a breath during pressure-targeted ventilation. This has been noted with Vyaire LTV-1000 ventilator in a clinical situation.[10] Autotriggering occasionally occurs in this same ventilator. These two phenomena can be prevented in most cases by adding about 2 inches of corrugated tubing between the Y-connector and endotracheal tube (or between the HME and the endotracheal tube) but must be accounted for as additional V_{Dmech}.

Final Alveolar Ventilation

During VC-CMV (A/C), $\dot{V}_A$ is calculated by multiplying the number of breaths counted for 1 minute by the corrected V_T: $\dot{V}_A = (V_T - V_{Danat} - \text{Added } V_{Dmech}) \times f$. When a patient is on VC-IMV, the mandatory rate and volume delivery must be calculated separately from the patient's spontaneous rate and volume; these values are then added to determine the total $\dot{V}_E$ (Box 8.6).

MONITORING AIRWAY PRESSURES

All positive pressure ventilators have a pressure monitor or display that continuously shows the upper airway pressure. The pressure monitor is probably most accurate when it shows pressures