the pressure applied at the mouth or upper airway is +15 cm H_2O and the pressure in the alveolus is zero (end exhalation), the gradient between the mouth and the lung is $P_{TA} = P_{awo} - P_{alv} = 15 - (0), = 15$ cm H_2O. Thus air will flow into the lung (see Table 1.1).

At any point during inspiration, the inflating pressure at the upper (proximal) airway equals the sum of the pressures required to overcome the resistance of the airways and the elastance of the lung and chest wall. During inspiration, the pressure in the alveoli progressively builds and becomes more positive. The resultant positive alveolar pressure is transmitted across the visceral pleura, and the intrapleural space may become positive at the end of inspiration (Fig. 1.8).

At the end of inspiration, the ventilator stops delivering positive pressure. Mouth pressure returns to ambient pressure (zero or atmospheric). Alveolar pressure is still positive, which creates a gradient between the alveolus and the mouth, and air flows out of the lungs. See Table 1.2 for a comparison of the changes in airway pressure gradients during passive spontaneous ventilation.

High-Frequency Ventilation

High-frequency ventilation uses above-normal ventilating rates with below-normal ventilating volumes. Three types of high-frequency ventilation strategies are available: **high-frequency jet ventilation** (HFJV), which uses frequencies from 4 to 10 Hz to provide rates between about 100 and 400 to 600 breaths/min; **high-frequency oscillatory ventilation**, which uses frequencies 3 to 15 Hz (180 to 900 cycles per/min); and **high-frequency percussive ventilation** (HFPV). In clinical practice, the various types of high-frequency ventilation are better defined by the type of ventilatory strategy used rather than the specific rates of each.

HFJV involves delivering pressurized jets of gas into the lungs at high frequencies (i.e., 4 to 11 Hz or cycles per second). HFJV is accomplished using a specially designed endotracheal tube adaptor and a nozzle or an injector; the small-diameter tube creates a high-velocity jet of air that is directed into the lungs. Exhalation is passive.

High-frequency oscillatory ventilation ventilators use either a small piston or a device similar to a stereo speaker to deliver gas in a "to-and-fro" motion, pushing gas in during inspiration and drawing gas out during exhalation. Ventilation with high-frequency oscillation has been used primarily in infants with respiratory distress and in adults or infants with open air leaks, such as **bronchopleural fistulas.**

HFPV was designed and developed by Forrest M. Bird, a pioneer in mechanical ventilation technology. Bird's intent was to incorporate the most effective characteristics of a conventional ventilator and a jet ventilator. The principle of operation is to provide high-frequency ambient pressure pulses (100 to 900 cycles/sec) superimposed on conventional positive pressure breaths (5 to 30 cycles/min). Although HFPV is most often used with a mask or mouthpiece as a therapeutic airway clearance device to mobilize secretions by percussing the chest internally, it also can be used as a continuous mode of ventilation in children. chapters 22 and 23 provide additional details on the unique nature of this mode of ventilation.

DEFINITION OF PRESSURES IN POSITIVE PRESSURE VENTILATION

At any point in a breath cycle during mechanical ventilation, the clinician can check the **manometer,** or pressure gauge, of a

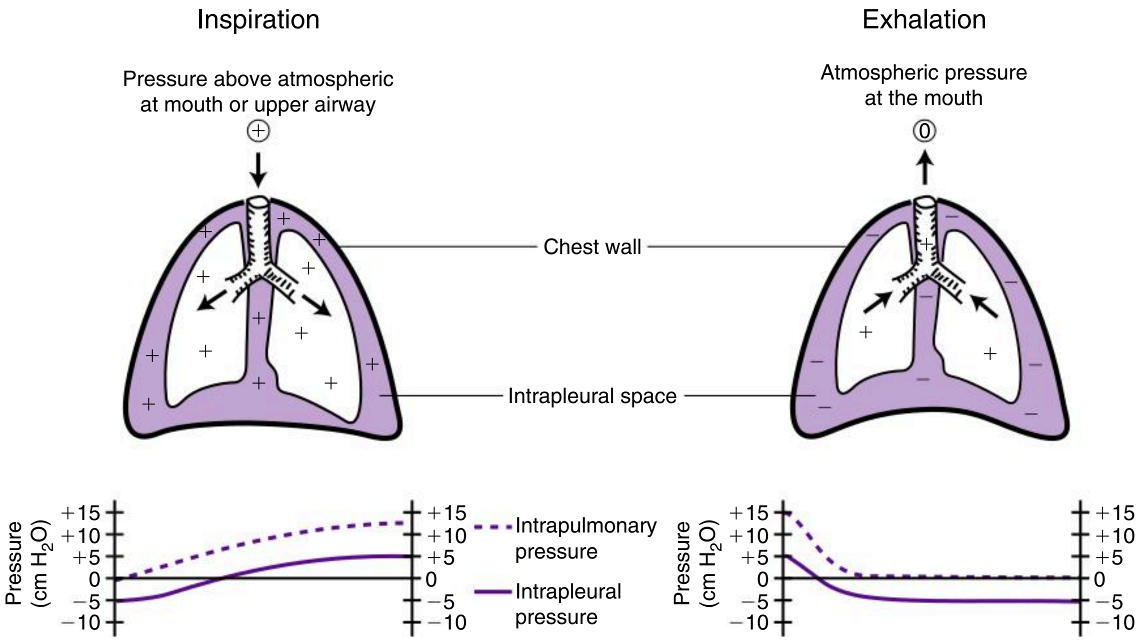


Fig. 1.8 Mechanics and pressure waves associated with positive pressure ventilation. During inspiration, as the upper airway pressure rises to about +15 cm H_20 (not shown), the alveolar (intrapulmonary) pressure is zero; as a result, air flows into the lungs until the alveolar pressure rises to about +9 to +12 cm H_20. The intrapleural pressure rises from about 5 cm H_20 before inspiration to about +5 cm H_20 at the end of inspiration. Flow stops when the ventilator cycles into exhalation. During exhalation, the upper airway pressure drops to zero as the ventilator stops delivering flow. The alveolar (intrapulmonary) pressure drops from about +9 to +12 cm H_20 to 0 as the chest wall and lung tissue recoil to their normal resting position; as a result, air flows out of the lungs. The intrapleural pressure returns to −5 cm H_20 during exhalation.

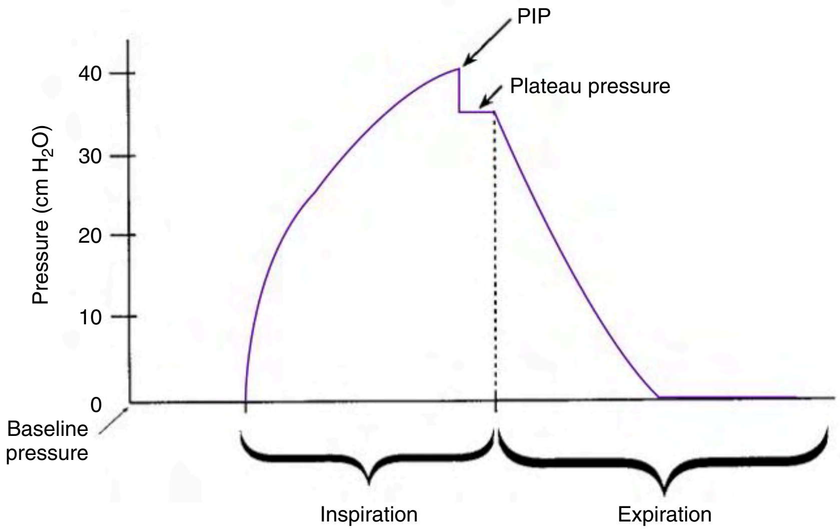


Fig. 1.9 Graph of upper-airway pressures that occur during a positive pressure breath. Pressure rises during inspiration to the peak inspiratory pressure (PIP). With a breath hold, the plateau pressure can be measured. Pressures fall back to baseline during expiration.

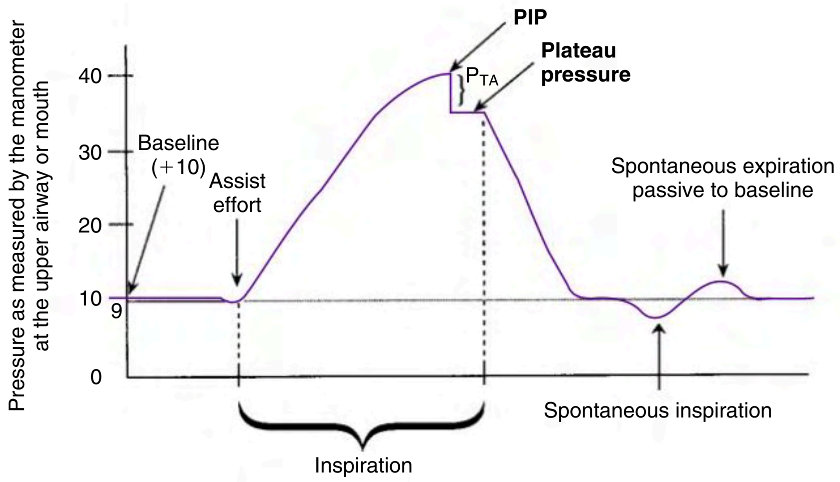


Fig. 1.10 Graph of airway pressures that occur during a mechanical positive pressure breath and a spontaneous breath. Both show an elevated baseline (positive end-expiratory pressure [PEEP] is +10 cm H_2O). To assist a breath, the ventilator drops the pressure below baseline by 1 cm H_2O. The assist effort is set at +9 cm H_2O. *PIP,* Peak inspiratory pressure; *P_{TA},* transairway pressure. (See text for further explanation.)

ventilator to determine the airway pressure present at that moment. This reading is measured either close to the mouth (proximal airway pressure) or on the inside of the ventilator, where it closely estimates the airway opening pressure.* A graph can be drawn to represent each of the points in time during the breath cycle showing pressure as it occurs over time. In the following section, each portion of the graphed pressure or time curve is reviewed. These pressure points provide information about the mode of ventilation and can be used to calculate a variety of parameters to monitor patients receiving mechanical ventilation.

*During mechanical ventilation, proximal airway pressure is not typically measured at the airway opening because of accumulation of secretions and technical errors can alter sensor measurements. Current-generation intensive care unit mechanical ventilators measure airway pressure (P_{aw}) using a sensor positioned proximal to the expiratory valve, which is closed during the inspiration.[2] The ventilator manometer pressure displayed on the user interface of the ventilator is typically designated as airway pressure (P_{aw}).[2]

Baseline Pressure

Airway pressures are measured relative to a baseline value. In Fig. 1.9, the baseline pressure is zero (or atmospheric), which indicates that no additional pressure is applied at the airway opening during expiration and before inspiration.

If the baseline pressure is higher than zero, such as when the ventilator operator selects a higher pressure to be present at the end of exhalation, this is called **positive end-expiratory pressure** (PEEP) (Fig. 1.10). When PEEP is set, the ventilator prevents the patient from exhaling to zero (atmospheric pressure). PEEP therefore increases the volume of gas remaining in the lungs at the end of a normal exhalation; that is, PEEP increases the functional residual capacity. PEEP applied by the operator is referred to as **extrinsic PEEP**. **Auto-PEEP** (or intrinsic PEEP), which is a potential side effect of positive pressure ventilation, occurs when air is accidentally trapped in the lung. **Intrinsic PEEP** typically occurs when a patient does not have enough time to exhale completely before the ventilator delivers another breath.

Peak Pressure

During positive pressure ventilation, the manometer rises progressively to a **peak pressure** (P_{Peak}). This is the highest pressure recorded at the end of inspiration. P_{Peak} is also called **peak inspiratory pressure** (PIP) or **peak airway pressure** (see Fig. 1.9).

The pressures measured during inspiration are the sum of two pressures: the pressure required to force the gas through the resistance of the airways (P_{TA}) and the pressure of the gas volume as it fills the alveoli (P_{alv}).*

Plateau Pressure

Another valuable pressure measurement is the plateau pressure. The plateau pressure is measured after a breath has been delivered to the patient and before exhalation begins. Exhalation is prevented by the ventilator for a brief moment (0.5 to 1.5 s). To obtain this measurement, the ventilator operator normally selects a control marked "inflation hold" or "inspiratory pause."

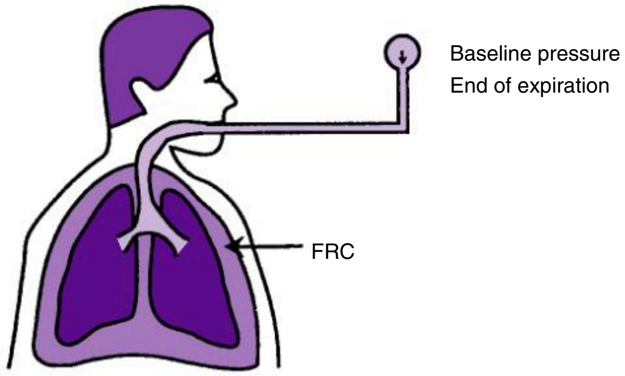
Plateau pressure measurement is similar to holding the breath at the end of inspiration. At the point of breath holding, the pressures inside the alveoli and mouth are equal (i.e., no gas flow). However, the relaxation of the respiratory muscles and the elastic recoil of the lung tissues are exerting force on the inflated lungs. This creates a positive pressure, which can be read on the ventilator manometer as a positive pressure. Because it occurs during a breath hold or pause, the manometer reading remains stable and "plateaus" at a certain value (see Figs. 1.9 through 1.11). It is important to note that the plateau pressure reading will be inaccurate if the patient is actively breathing during the measurement.

Plateau pressure is often used interchangeably with **alveolar pressure** (P_{alv}) and **intrapulmonary pressure**. Although these terms are related, they are not synonymous. The plateau pressure reflects the effect of the elastic recoil on the gas volume inside the alveoli and any pressure exerted by the volume in the ventilator circuit that is acted on by the recoil of the plastic circuit.

Pressure at the End of Exhalation

As previously mentioned, air can be trapped in the lungs during mechanical ventilation if adequate time is not allowed for exhalation. The most effective method to prevent this complication is to monitor the pressure in the ventilator circuit at the end of exhalation. If extrinsic PEEP has not been added and the baseline pressure is greater than zero (i.e., atmospheric pressure), air trapping, or auto-PEEP, is present (this concept is covered in greater detail in Chapter 17).

*At any point during inspiration, gauge pressure equals $P_{TA} + P_{alv}$. The gauge pressure also will include pressure associated with PEEP.



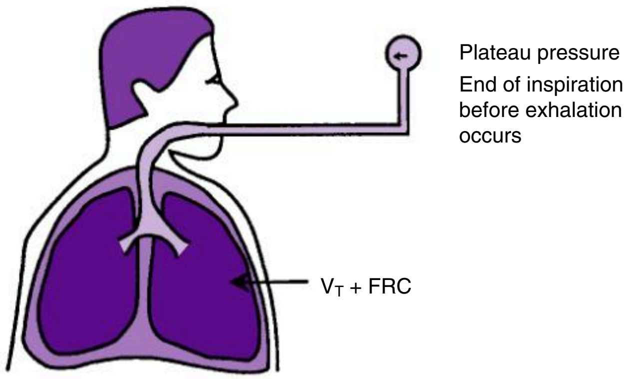


Fig. 1.11 At baseline pressure (end of exhalation), the volume of air remaining in the lungs is the functional residual capacity (FRC). At the end of inspiration, before exhalation starts, the volume of air in the lungs is the tidal volume (V_T) plus the FRC. The pressure measured at this point, with no flow of air, is the plateau pressure.

SUMMARY

- Spontaneous ventilation is accomplished by contraction of the muscles of inspiration, which causes expansion of the thorax, or chest cavity. During mechanical ventilation, the mechanical ventilator provides some or all of the energy required to expand the thorax.
- For air to flow through a tube or airway, a pressure gradient must exist (i.e., pressure at one end of the tube must be higher than pressure at the other end of the tube). Air will always flow from the high-pressure point to the low-pressure point.
- Several terms are used to describe airway opening pressure, including *mouth pressure, upper-airway pressure, mask pressure,* or *proximal airway pressure.* Unless pressure is applied at the airway opening, P_{awo} is zero, or atmospheric pressure.
- Intrapleural pressure is the pressure in the potential space between the parietal and visceral pleurae.
- The plateau pressure, which is sometimes substituted for alveolar pressure, is measured during a breath-hold maneuver during mechanical ventilation, and the value is read from the ventilator manometer.
- Four basic pressure gradients are used to describe normal ventilation: transairway pressure, transthoracic pressure, transpulmonary pressure, and transrespiratory pressure.

- Two types of forces oppose inflation of the lungs: elastic forces and frictional forces.
- Elastic forces arise from the elastance of the lungs and chest wall.
- Frictional forces are the result of two factors: the resistance of the tissues and organs as they become displaced during breathing, and the resistance to gas flow through the airways.
- Compliance and resistance are often used to describe the mechanical properties of the respiratory system. In the clinical setting, compliance measurements are used to describe the elastic forces that oppose lung inflation; airway resistance is a measurement of the frictional forces that must be overcome during breathing.
- The resistance to airflow through the conductive airways *(flow resistance)* depends on the gas viscosity, gas density, length and diameter of the tube, and flow rate of the gas through the tube.
- The product of compliance (C) and resistance (R) is called a *time constant.* For any value of C and R, the time constant approximates the time in seconds required to inflate or deflate the lungs.
- Calculation of time constants is important when setting the ventilator's inspiratory time and expiratory time.
- Three basic methods have been developed to mimic or replace the normal mechanisms of breathing: negative pressure ventilation, positive pressure ventilation, and high-frequency ventilation.

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

1. Using Fig. 1.12, draw a graph and show the changes in the intrapleural and alveolar (intrapulmonary) pressures that occur during spontaneous ventilation and during a positive pressure breath. Compare the two.
2. Convert 5 mm Hg to cm H_2O.
3. Which of the lung units in Fig. 1.13 receives more volume during inspiration? Why? Which has a longer time constant?
4. In Fig. 1.14, which lung unit fills more quickly? Which has the shorter time constant? Which receives the greatest volume?
5. This exercise is intended to provide the reader with a greater understanding of time constants. Calculate the following six possible combinations. Then rank the lung units from the slowest filling to the most rapid filling. Because resistance is seldom better than normal, no example is given that is lower than normal for this particular parameter. (Normal values have been simplified to make calculations easier.)
   A. Normal lung unit: $C_S = 0.1$ L/cm H_2O; $R_{aw} = 1$ cm H_2O/(L/s)
   B. Lung unit with reduced compliance and normal airway resistance: $C_S = 0.025$ L/cm H_2O; $R_{aw} = 1$ cm H_2O/(L/s)
   C. Lung unit with normal compliance and increased airway resistance: $C_S = 0.1$ L/cm H_2O; $R_{aw} = 10$ cm H_2O/(L/s)
   D. Lung unit with reduced compliance and increased airway resistance: $C_S = 0.025$ L/cm H_2O; $R_{aw} = 10$ cm H_2O/(L/s)
   E. Lung unit with increased compliance and increased airway resistance: $C_S = 0.15$ L/cm H_2O; $R_{aw} = 10$ cm H_2O/(L/s)
   F. Lung unit with increased compliance and normal airway resistance: $C_S = 0.15$ L/cm H_2O; $R_{aw} = 1$ cm H_2O/(L/s)
6. 1 mm Hg =:
   A. 1.63 cm H_2O
   B. 1.30 atm
   C. 1.36 cm H_2O
   D. 1034 cm H_2O
7. The pressure difference between the alveolus (P_{alv}) and the body surface (P_{bs}) is called:
   A. Transpulmonary pressure
   B. Transrespiratory pressure
   C. Transairway pressure
   D. Transthoracic pressure

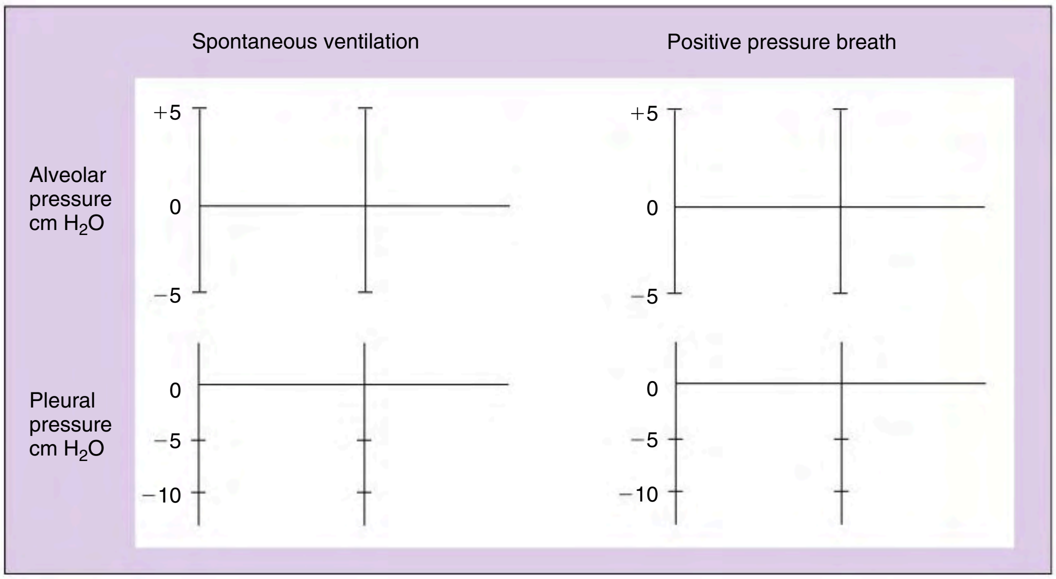


Fig. 1.12 Graphing of alveolar and pleural pressures for spontaneous ventilation and a positive pressure breath.

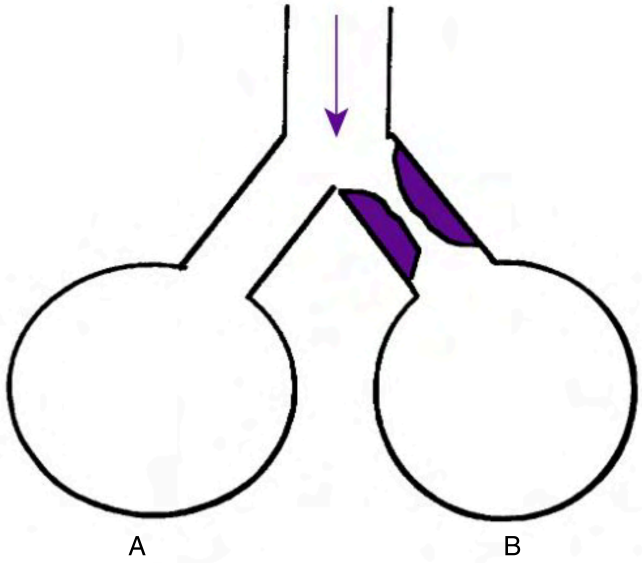


Fig. 1.13 Lung unit (A) is normal. Lung unit (B) shows an obstruction in the airway.

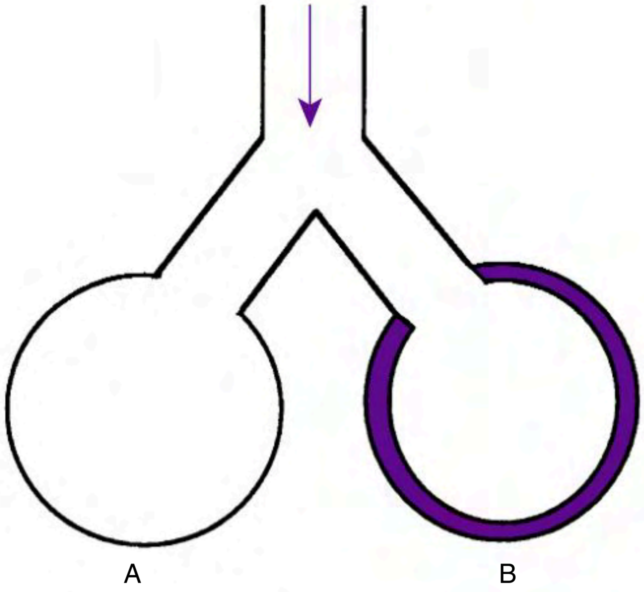


Fig. 1.14 Lung unit (A) is normal. Lung unit (B) shows decreased compliance (see text).

8. Define elastance.
A. Ability of a structure to stretch
B. Ability of a structure to return to its natural shape after stretching
C. Ability of a structure to stretch and remain in that position
D. None of the above

9. Which of the following formulas is used to calculate compliance?
A. $\Delta V = C/\Delta P$
B. $\Delta P = \Delta V/C$
C. $C = \Delta V/\Delta P$
D. $C = \Delta P/\Delta V$

10. Another term for airway pressure is:
A. Mouth pressure
B. Airway opening pressure
C. Mask pressure
D. All of the above

11. Intraalveolar pressure (in relation to atmospheric pressure) at the end of inspiration during a normal quiet breath is approximately:
A. -5 cm H_2O
B. 0 cm H_2O
C. $+5$ cm H_2O
D. 10 cm H_2O

12. Which of the following is associated with an increase in airway resistance?
A. Decreasing the flow rate of gas into the airway
B. Reducing the density of the gas being inhaled
C. Increasing the diameter of the endotracheal tube
D. Reducing the length of the endotracheal tube

13. Which of the following statements is true regarding negative pressure ventilation?
A. Chest cuirass is often used in the treatment of hypovolemic patients.
B. Tank respirators are particularly useful in the treatment of burn patients.
C. The incidence of alveolar barotrauma is higher with these devices compared with positive pressure ventilation.
D. These ventilators mimic normal breathing mechanics.

14. PEEP is best defined as:
A. Zero baseline during exhalation on a positive pressure ventilator
B. Positive pressure during inspiration that is set by the person operating the ventilator
C. Negative pressure during exhalation on a positive pressure ventilator
D. Positive pressure at the end of exhalation on a mechanical ventilator

15. Which of the following statements is true regarding plateau pressure?
A. Plateau pressure normally is zero at end inspiration.
B. Plateau pressure is used as a measure of alveolar pressure.
C. Plateau pressure is measured at the end of exhalation.
D. Plateau pressure is a dynamic measurement.

16. One time constant should allow approximately what percentage of a lung unit to fill?
A. 37%
B. 100%
C. 63%
D. 85%

17. A patient has a PIP of 30 cm H_2O and a P_{plat} of 20 cm H_2O. Ventilator flow is set at a constant value of 30 L/min. What is the transairway pressure?
A. 1 cm H_2O
B. 0.33 cm H_2O
C. 20 cm H_2O
D. 10 cm H_2O

References

1. Kacmarek RM: Physiology of ventilatory support. In Kacmarek RM, Stoller JK, Heuer AJ, editors: *Egan's fundamentals of respiratory care*, ed 12, St. Louis, MO, 2020, Elsevier, pp 1013–1052.
2. Hess DR: Respiratory mechanics in mechanically ventilated patients, *Respir Care* 59(11):1773–1794, 2014.
3. Levitzky MG: *Pulmonary physiology*, ed 9, New York, NY, 2018, McGraw-Hill Education.
4. Campbell EJM, Agostoni E, Davis JN: *The respiratory muscles, mechanics and neural control*, ed 2, London, 1970, Whitefriars Press.
5. Chatburn RL, Volsko TA: Mechanical ventilators. In Kacmarek RM, Stoller JK, Heuer AJ, editors: *Egan's fundamentals of respiratory care*, ed 12, St. Louis, MO, 2020, Elsevier.
6. Brunner JX, Laubschre TP, Banner MJ, Iotti G, Braschi A: Simple method to measure total expiratory time constant based on passive expiratory flow-volume curve, *Crit Care Med* 23(6):1117–1122, 1995.
7. Marks A, Asher J, Bocles L, et al.: A new ventilator assister for patients with respiratory acidosis, *N Engl J Med* 268(2):61–68, 1963.
8. Hill NS: Clinical applications of body ventilators, *Chest* 90:897–905, 1986.
9. Kirby RR, Banner MJ, Downs JB: *Clinical applications of ventilatory support*, ed 2, New York, NY, 1990, Churchill Livingstone.
10. Corrado A, Gorini M: Negative pressure ventilation. In Tobin MJ, editor: *Principles and practice of mechanical ventilation*, ed 3, New York, NY, 2013, McGraw-Hill.
11. Holtackers TR, Loosbrook LM, Gracey DR: The use of the chest cuirass in respiratory failure of neurologic origin, *Respir Care* 27(3):271–275, 1982.
12. Cairo JM: *Mosby's respiratory care equipment*, ed 11, St. Louis, MO, 2022, Elsevier.
13. Splaingard ML, Frates RC, Jefferson, et al.: Home negative pressure ventilation: report of 20 years of experience in patients with neuromuscular disease, *Arch Phys Med Rehabil* 66:239–242, 1983.

CHAPTER 2

How Ventilators Work

OUTLINE

KEY TERMS

- Closed-loop system
- Control system
- Double-circuit ventilator
- Drive mechanism
- External circuit
- Internal pneumatic circuit
- Mandatory minute ventilation
- Microprocessors
- Open-loop system
- Patient circuit
- Single-circuit ventilator
- User interface

LEARNING OBJECTIVES

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

1. List the basic types of power sources used for mechanical ventilators.
2. Give examples of ventilators that use an electrical and a pneumatic power source.
3. Explain the difference in function between positive and negative pressure ventilators.
4. Distinguish between a closed-loop and an open-loop system.
5. Define *user interface.*
6. Describe a ventilator's internal and external pneumatic circuits.
7. Discuss the difference between a single-circuit and a double-circuit ventilator.
8. Identify the components of an external circuit (patient circuit).
9. Explain the function of an externally mounted exhalation valve.
10. Compare the functions of the three types of volume displacement drive mechanisms.
11. Describe the function of the proportional solenoid valve.

Clinicians caring for critically ill patients receiving ventilatory support must have a basic understanding of the principles of operation of mechanical ventilators. This understanding should focus on patient-ventilator interactions (i.e., how the ventilator interacts with the patient's breathing pattern and how the patient's lung condition can affect the ventilator's performance). Many different types of ventilators are available for adult, pediatric, and neonatal care in hospitals; for patient transport; and for home care. Mastering the complexities of each of these devices may seem overwhelming at times. Fortunately, ventilators have a number of properties in common, which allow them to be described and grouped accordingly.

An excellent way to gain an overview of a particular ventilator is to study how it functions. Part of the problem with this approach, however, is that the terminology used by manufacturers and authors varies considerably. The purpose of this chapter is to address these terminology differences and provide an overview of ventilator function as it relates to current standards.[1-3] It does not attempt to review all available ventilators. For models not covered in this discussion, the reader should consult other texts and the literature provided by the manufacturer.[3] The description of the "hardware" components of mechanical ventilators presented in this chapter should provide clinicians with a better understanding of the principles of operation of these devices.

HISTORICAL PERSPECTIVE ON VENTILATOR CLASSIFICATION

The earliest commercially available ventilators used in the clinical setting (e.g., Mörch, Emerson Post-Op) were developed in the 1950s and 1960s. These devices were classified originally according to a system developed by Mushin and colleagues.[4] Technological advances made during the past 50 years have dramatically changed the way ventilators operate, and these changes required an updated approach to ventilator classification. The following discussion is based on an updated classification system proposed by Chatburn.[1] Chatburn's approach to classifying ventilators uses engineering and clinical principles to describe ventilator function.[2] Although this classification system provides a good foundation for discussing various aspects of mechanical ventilation, many clinicians still rely on the earlier classification system to describe basic ventilator operation. Both classification systems are referenced when necessary in the following discussion to describe the principles of operation of commonly used mechanical ventilators.

INTERNAL FUNCTION

A ventilator probably can be easily understood if it is pictured as a "black box." The ventilator is plugged into an electrical outlet or a high-pressure gas source, and gas comes out the other side and is delivered to the patient. The person who operates the ventilator inputs settings using a touch panel or dials on a control panel (**user interface**) to establish the pressure and pattern of gas flow delivered by the machine. Inside the ventilator, a **control system** interprets the operator's settings and produces and regulates the desired output. In the discussion that follows, specific characteristics of the various components of a typical commercially available mechanical ventilator are discussed. Box 2.1 provides a summary of the major components of a ventilator.

POWER SOURCE OR INPUT POWER

The ventilator's power source provides the energy that enables the machine to perform the work of ventilating the patient. As discussed in Chapter 1, ventilation can be achieved using either positive or negative pressure. The power used by a mechanical ventilator to generate this positive or negative pressure may be provided by an electrical or pneumatic (compressed gas) source.

Electrically Powered Ventilators

Electrically powered ventilators rely entirely on electricity from a standard electrical outlet (110–115 V, 60-Hz alternating current in the United States; higher voltages [220 V, 50 Hz] in other countries), or a rechargeable battery (direct current) may be used. Battery power is typically used for a short period, such as for transporting a ventilated patient, or in homecare therapy as a backup power source if the home's electricity fails.

An on/off switch controls the main electrical power source. The electricity provides the energy to operate motors, electromagnets, potentiometers, rheostats, and **microprocessors**, which, in turn, control the timing mechanisms for inspiration and expiration, gas flow, and alarm systems. Electrical power also may be used to operate devices such as fans, bellows, solenoids, and transducers. All these devices help ensure a controlled pressure and gas flow to the patient. Examples of electrically powered and controlled ventilators are listed in Box 2.2.

Pneumatically Powered Ventilators

Current-generation intensive care unit (ICU) ventilators are typically pneumatically powered devices. These machines use one or two 50-psi gas sources and have built-in internal reducing valves so that the operating pressure is lower than the source pressure.

Pneumatically powered ventilators are classified according to the mechanism used to control gas flow. Two types of devices are available: pneumatic ventilators and fluidic ventilators. Pneumatic ventilators use needle valves, Venturi entrainers (injectors), flexible diaphragms, and spring-loaded valves to control flow, volume delivery, and inspiratory and expiratory function (Fig. 2.1). The Bird Mark 7 ventilator, which was originally used for prolonged mechanical ventilation, is often cited as an example of a pneumatic ventilator. These devices also have been used to administer intermittent positive pressure breathing (IPPB) treatments. IPPB treatments involve the delivery of aerosolized medications to spontaneously breathing patients with reduced ventilatory function (e.g., chronic obstructive pulmonary disease patients).

Fluidic ventilators rely on special principles to control gas flow, specifically the principles of wall attachment (i.e., Coanda effect) and beam deflection. Fig. 2.2 shows the basic components and summary of the principle of operation for a fluidic system. An example of a ventilator that uses fluidic control circuits is the Bio-Med MVP-10. (Fluidic circuits are analogous to electronic logic circuits.) Fluidic systems are occasionally used to provide ventilation to patients in the acute care setting.[3]

Most pneumatically powered ICU ventilators also have an electrical power source incorporated into their design to energize a computer that controls the ventilator functions. Notice that the gas sources, mixtures of air and oxygen, supply the power for ventilator function and allow for a variable fractional inspired oxygen concentration (F_{IO_2}). The electrical power is required for operation of the computer microprocessor, which controls capacitors, solenoids, and electrical switches that regulate the phasing of inspiration and expiration, and the monitoring of gas flow. The ventilator's preprogrammed ventilator modes are stored in the microprocessor's read-only memory, which can be updated rapidly by installing new software programs. Random access memory,

BOX 2.1 Components of a Ventilator

1. Power source or input power (electrical or gas source)
   a. Electrically powered ventilators
   b. Pneumatically powered ventilators
2. Positive or negative pressure generator
3. Control systems and circuits
   a. Open-loop and closed-loop systems to control ventilator function
   b. Control panel (user interface)
   c. Pneumatic circuit
4. Power transmission and conversion system
   a. Volume displacement, pneumatic designs
   b. Flow-control valves
5. Output (pressure, volume, and flow waveforms)

BOX 2.2 Examples of Electrically Powered Ventilators

LTV 1150, 1200 Ventilator (Vyaire Medical, Mettawa, Ill.)
Newport HT70 (Medtronic Minimally Invasive Therapies, Minneapolis, Minn.)

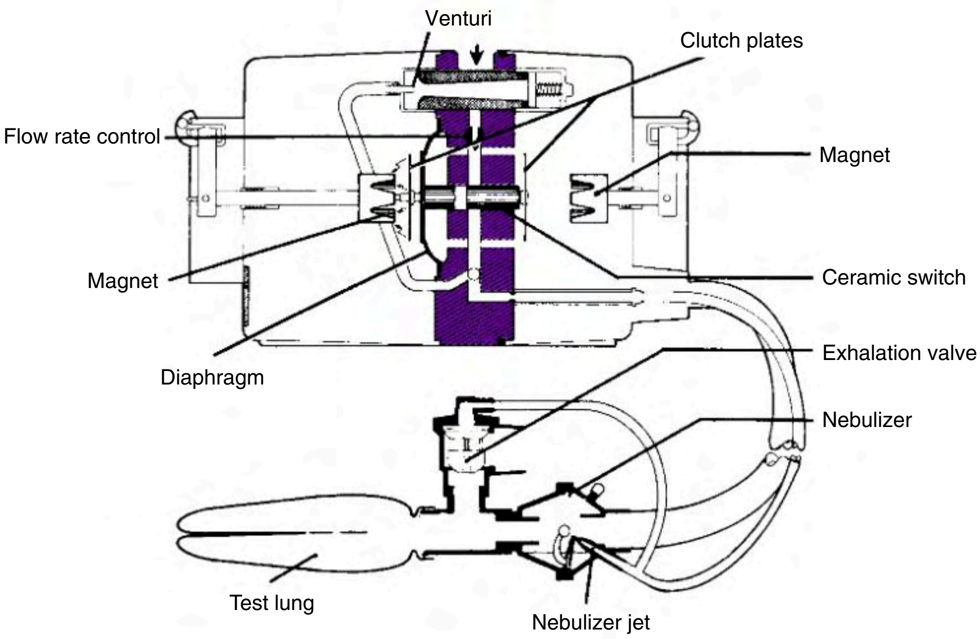


Fig. 2.1 The Bird Mark 7 is an example of a pneumatically powered ventilator. (Courtesy CareFusion, Viasys Corp., San Diego, Calif.)

***Key Point* 2.1** Pneumatically powered, microprocessor-controlled ventilators rely on pneumatic power (i.e., the 50-psi gas sources) to provide the energy to deliver the breath. Electrical power from an alternating current wall-socket or from a direct-current battery power source provides the energy for a computer microprocessor that controls the internal function of the machine.

Case Study 2.1

Ventilator Selection

A patient who requires continuous ventilatory support is being transferred from the intensive care unit to a general care patient room. The general care hospital rooms are equipped with piped-in oxygen but not piped-in air. What type of ventilator would you select for this patient?

which is also incorporated into the ventilator's central processing unit, is used for temporary storage of data, such as pressure and flow measurements and airway resistance and compliance (Key Point 2.1).

Case Study 2.1 provides an exercise in selecting a ventilator with a specific power source.

Positive and Negative Pressure Ventilators

As discussed in Chapter 1, gas flow into the lungs can be accomplished by using two different methods of changing the transrespiratory pressure gradient (pressure at the airway opening minus pressure at the body surface [$P_{awo} - P_{bs}$]). A ventilator can change the transrespiratory pressure gradient by altering either the pressure applied at the airway opening (P_{awo}) or the pressure around the body surface (P_{bs}). With positive pressure ventilators, gas flows into the lung because the ventilator establishes a pressure gradient by generating a positive pressure at the airway opening (Fig. 2.3A). In contrast, a negative pressure ventilator generates a negative pressure at the body surface that is transmitted to the pleural space and then to the alveoli (see Fig. 2.3B).

CONTROL SYSTEMS AND CIRCUITS

The control system (control circuit), or the decision-making system that regulates ventilator function internally, can use mechanical or electrical devices, electronics, pneumatics, fluidics, or a combination of these.

Open-Loop and Closed-Loop Systems to Control Ventilator Function

Advances in microprocessor technology have allowed ventilator manufacturers to develop a new generation of ventilators that use feedback loop systems. Most ventilators that are *not* microprocessor controlled are called **open-loop systems**. The operator sets a control (e.g., tidal volume), and the ventilator delivers that volume to the patient circuit. This is called an open-loop system because the ventilator cannot be programmed to respond to changing conditions. If gas leaks out of the patient circuit (and therefore does not reach the patient), the ventilator cannot adjust its function to correct for the leakage. It simply delivers a set volume and does not measure or change it (Fig. 2.4A).

Closed-loop systems are often described as "intelligent" systems because they compare the set control variable with the measured control variable, which in turn allows the ventilator to respond to changes in the patient's condition. For example, some closed-loop systems are programmed to compare the tidal volume setting with the measured tidal volume exhaled by the patient. If the two differ, the control system can alter the volume delivery (see Fig. 2.4B).[5-7]

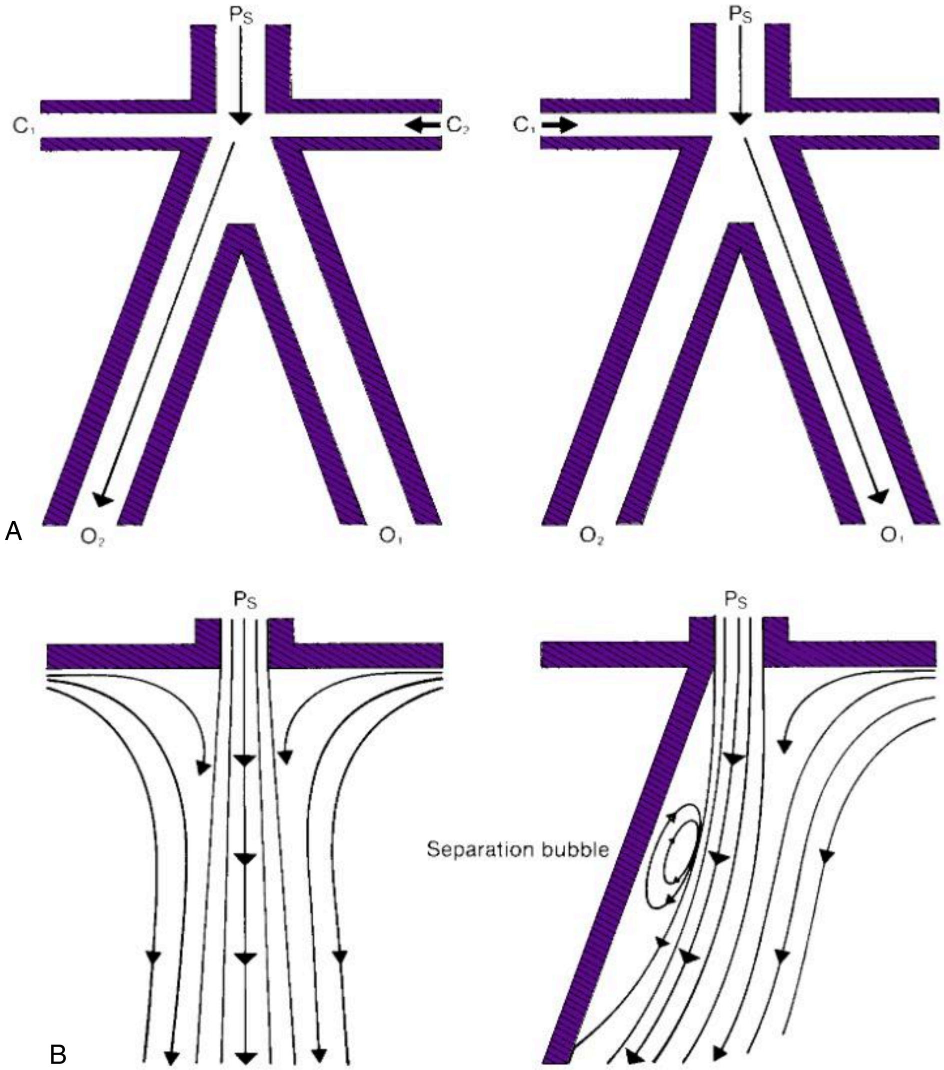


Fig. 2.2 Basic components of fluid logic (fluidic) pneumatic mechanisms. (A) Example of a flip-flop valve (beam deflection). When a continuous pressure source (P_S at inlet A) enters, wall attachment occurs and the output is established (O_2). A control signal (single gas pulse) from C_1 deflects the beam to outlet O_1. (B) The wall attachment phenomenon, or *Coandă effect,* is demonstrated. A turbulent jet flow causes a localized drop in lateral pressure and draws in air *(figure on left)*. When a wall is adjacent, a low-pressure vortex bubble (separation bubble) is created and bends the jet toward the wall *(figure on right)*. (From Dupuis YG: *Ventilators: theory and clinical applications,* ed 2, St. Louis, MO, 1992, Mosby.)

Mandatory minute ventilation is a good example of a closed-loop system. The operator selects a minimum minute ventilation setting that is lower than the patient's spontaneous minute ventilation. The ventilator monitors the patient's spontaneous minute ventilation, and if it falls below the operator's set value, the ventilator increases its output to meet the minimum set minute ventilation (Critical Care Concept 2.1).

Control Panel (User Interface)

The control panel, or *user interface,* is located on the surface of the ventilator and is monitored and set by the ventilator operator. The internal control system reads and uses the operator's settings to control the function of the drive mechanism. The control panel has various knobs or touch pads for setting components, such as

CRITICAL CARE CONCEPT 2.1

Open-Loop or Closed-Loop

A ventilator is programmed to monitor S_pO_2. If the S_pO_2 drops below 90% for longer than 30 seconds, the ventilator is programmed to activate an audible alarm that cannot be silenced and a flashing red visual alarm. The ventilator is also programmed to increase the oxygen percentage to 100% until the alarms have been answered and deactivated. Is this a closed-loop or an open-loop system? What are the potential advantages and disadvantages of using this type of system?

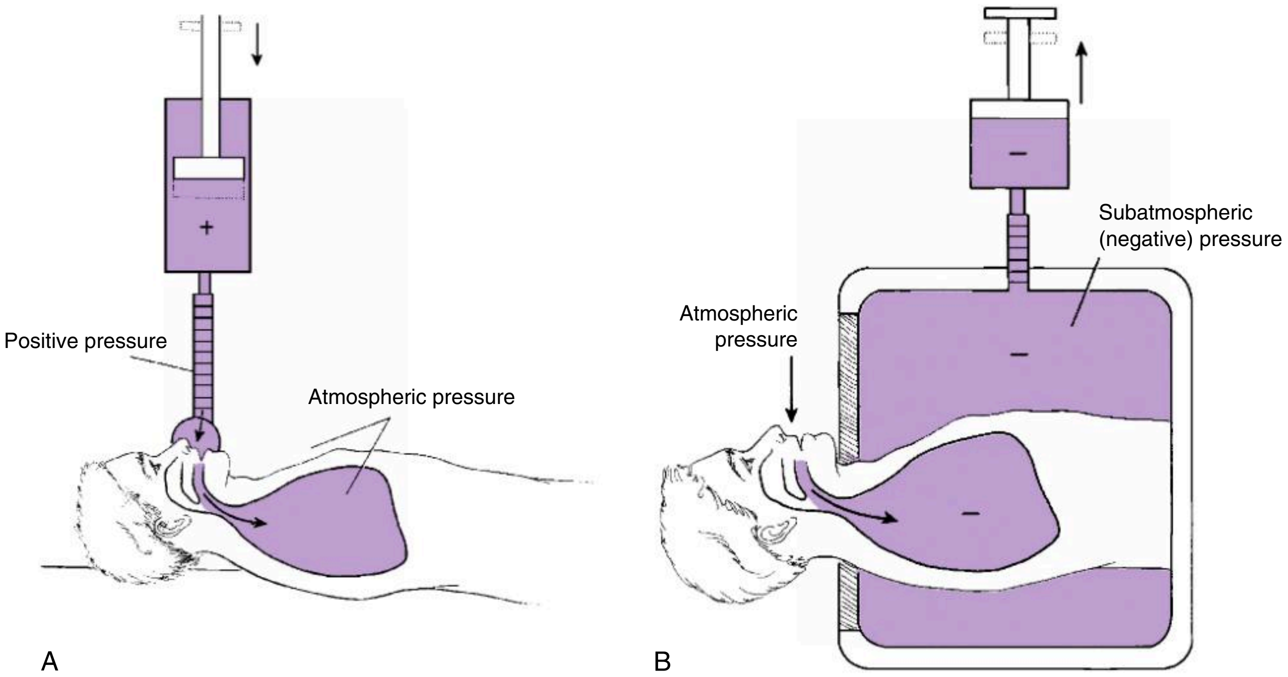


Fig. 2.3 (A) Application of positive pressure at the airway provides a pressure gradient between the mouth and the alveoli; as a result, gas flows into the lungs. (B) As subatmospheric pressure is applied around the chest wall, pressure drops in the alveoli and air flows into the lungs.

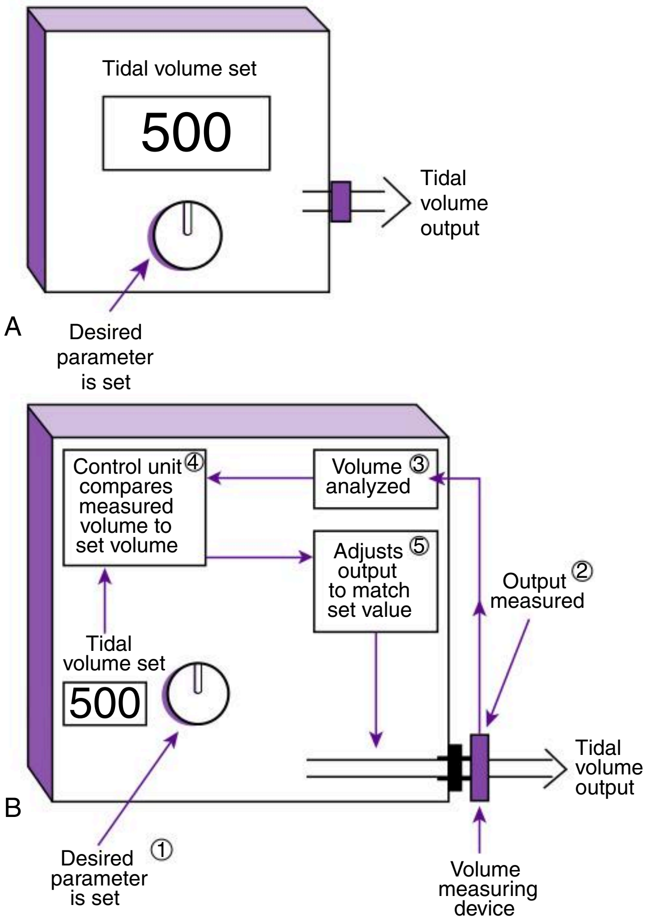


Fig. 2.4 (A) Open-loop system. (B) Closed-loop system using tidal volume as the measured parameter.

tidal volume, rate, inspiratory time, alarms, and F_{IO_2} (Fig. 2.5). These controls ultimately regulate four ventilatory variables: flow, volume, pressure, and time. The value for each of these can vary within a wide range, and the manufacturer provides a list of the potential ranges for each variable. For example, tidal volume may range from 200 to 2000 mL on an adult ventilator. The operator also can set alarms to respond to changes in a variety of monitored variables, particularly high and low pressure and low volume. (Alarm settings are discussed in more detail in Chapter 7.)

Pneumatic Circuit

A pneumatic circuit, or pathway, is a series of tubes that allow gas to flow inside the ventilator and between the ventilator and patient. The pressure gradient created by the ventilator with its power source generates the flow of gas. This gas flows through the pneumatic circuit en route to the patient. The gas first is directed from the generating source inside the ventilator through the **internal pneumatic circuit** to the ventilator's outside surface. Gas then flows through an **external circuit,** or **patient circuit,** into the patient's lungs. Exhaled gas passes through the expiratory limb of the external circuit and to the atmosphere through an exhalation valve.

Internal Pneumatic Circuit

If the ventilator's internal circuit allows the gas to flow directly from its power source to the patient, the machine is called a **single-circuit ventilator** (Fig. 2.6). The source of the gas may be either externally compressed gas or an internal pressurizing source, such as a compressor. Most ICU ventilators manufactured today are classified as single-circuit ventilators.

Another type of internal pneumatic circuit ventilator is the **double-circuit ventilator.** In these machines, the primary power source generates a gas flow that compresses a mechanism such as a *bellows* or *"bag-in-a-chamber."* The gas in the bellows or bag then

Fig. 2.5 User interface of the Medtronics PB 840 ventilator. (Courtesy Medtronics Minimally Invasive Therapies, Minneapolis, Minn.)

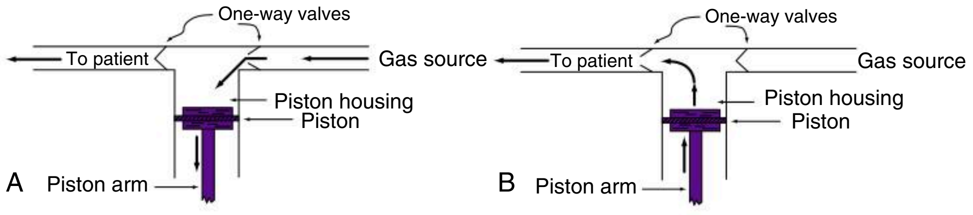


Fig. 2.6 Single-circuit ventilator. (A) Gases are drawn into the cylinder during the expiratory phase. (B) The piston moves upward into the cylinder during inspiration, sending gas directly to the patient circuit.

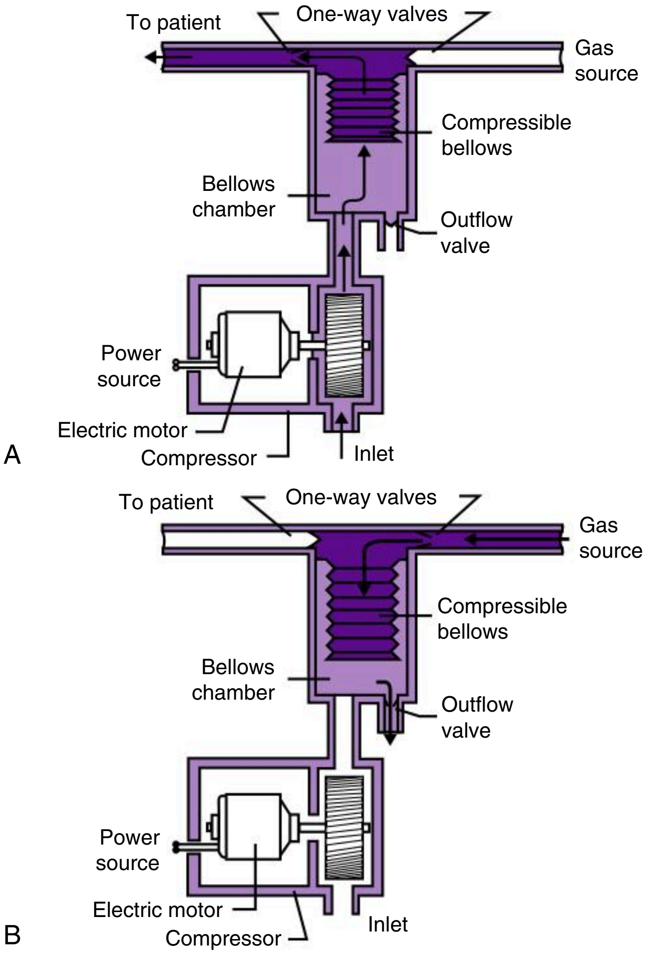


Fig. 2.7 Double-circuit ventilator. An electrical compressor produces a high-pressure gas source, which is directed into a chamber that holds a collapsible bellows. The bellows contains the desired gas mixture for the patient. The pressure from the compressor forces the bellows upward, resulting in a positive pressure breath (A). After delivery of the inspiratory breath, the compressor stops directing pressure into the bellows chamber and exhalation occurs. The bellows drops to its original position and fills with the gas mixture in preparation for the next breath (B).

***Key Point* 2.2** Most commercially available intensive care unit ventilators are single-circuit, microprocessor-controlled, positive pressure ventilators with closed-loop elements of logic in the control system.

flows to the patient. Fig. 2.7 illustrates the principle of operation of a double-circuit ventilator (Key Point 2.2).

External Pneumatic Circuit

The external pneumatic circuit, or patient circuit, connects the ventilator to the patient's artificial airway. This circuit must have several basic elements to provide a positive pressure breath (Box 2.3). Fig. 2.8 shows examples of two types of patient circuits. During inspiration, the expiratory valve closes so that gas can flow only into the patient's lungs.

In early-generation ventilators (e.g., the Bear 3), the exhalation valve was mounted in the main exhalation line of the patient circuit (see Fig. 2.8A). With this arrangement, an expiratory valve charge line, which powers the expiratory valve, also must be present. When the ventilator begins inspiratory gas flow through the main inspiratory tube, gas also flows through the charge line, closing the valve (see Fig. 2.8A). During exhalation, the flow from the ventilator stops, the charge line depressurizes, and the exhalation valve opens. Then the patient is able to exhale passively through the expiratory port. In most current ICU ventilators, the exhalation valve is located inside the ventilator and is not visible (see Fig. 2.8B). A mechanical device, such as a solenoid valve, typically is used to control these internally mounted exhalation valves (see the section on flow valves later in this chapter).

BOX 2.3 Basic Elements of a Patient Circuit

1. *Main inspiratory line:* Connects the ventilator output to the patient's airway adapter or connector
2. *Adapter:* Connects the main inspiratory line to the patient's airway (also called a *patient adapter* or *Y-connector* because of its shape)
3. *Expiratory line:* Delivers expired gas from the patient to the exhalation valve
4. *Expiratory valve:* Allows the release of exhaled gas from the expiratory line into the room air

Fig. 2.9 illustrates the various components typically included in a patient's circuit to optimize gas delivery and ventilator function. The most common adjuncts are shown in Box 2.4. Additional monitoring devices include graphic display screens, oxygen analyzers, pulse oximeters, capnographs (end-tidal CO_2 monitors), and flow and pressure sensors for monitoring lung compliance and airway resistance (for more detail about monitoring devices, see Chapter 10).

POWER TRANSMISSION AND CONVERSION SYSTEM

A ventilator's power source enables it to perform mechanical or pneumatic operations. The internal hardware that accomplishes the conversion of electrical or pneumatic energy into the mechanical energy required to deliver a breath to the patient is called the *power transmission and conversion system.* It consists of a **drive mechanism** and an output control mechanism.

The drive mechanism is a mechanical device that produces gas flow to the patient. An example of a drive mechanism is a piston powered by an electrical motor. The output control consists of one or more valves that regulate gas flow to the patient. From an engineering perspective, power transmission and conversion systems can be categorized as volume controllers or flow controllers.[2,7]

Compressors (Blowers)

An appreciation of how volume and flow controllers operate requires an understanding of compressors, or blowers. Compressors reduce internal volumes (compression) within the ventilator to generate a positive pressure required to deliver gas to the patient. Compressors may be piston driven, or they may use rotating blades (vanes), moving diaphragms, or bellows. Hospitals use large, piston-type, water-cooled compressors to supply wall gas outlets, which

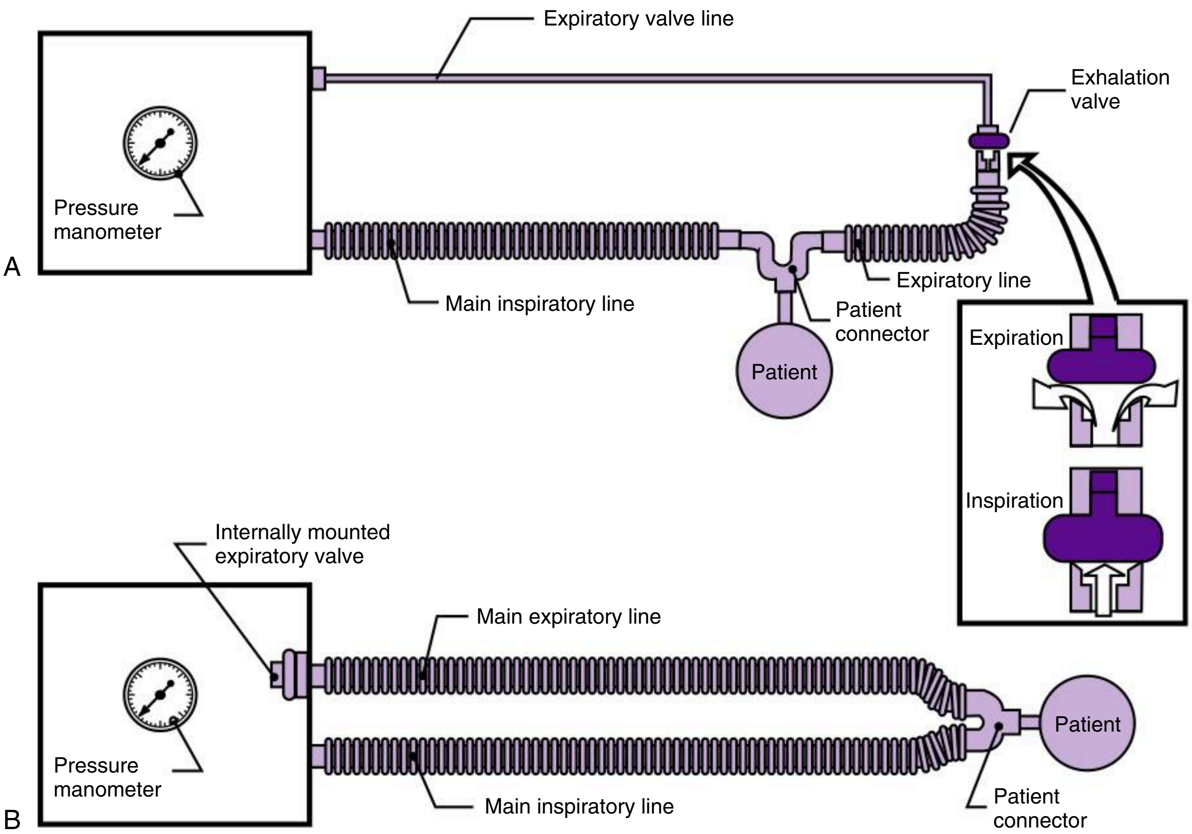


Fig. 2.8 Basic components of a patient circuit that are required for a positive pressure breath. (A) Ventilator circuit with an externally mounted expiratory valve. The cutaway shows a balloon-type expiratory valve. During inspiration, gas fills the balloon and closes a hole in the expiratory valve. Closing of the hole makes the patient circuit a sealed system. During expiration, the balloon deflates, the hole opens, and gas from the patient is exhaled into the room through the hole. (B) Ventilator circuit with an internally mounted exhalation valve. (From Cairo JM: *Mosby's respiratory care equipment,* ed 11, St. Louis, MO, 2021, Elsevier.)

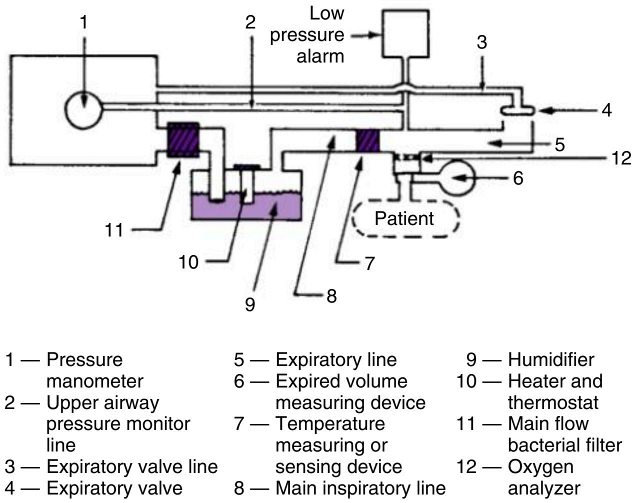


Fig. 2.9 A patient circuit with additional components required for optimal functioning during continuous mechanical ventilation.

many ventilators use as a power source. Some ventilators (e.g., Maquet Servo-i) have built-in compressors that can be used to power the ventilator if a wall gas outlet is not available.

BOX 2.4 Adjuncts Used With a Patient Circuit

1. A device to warm and humidify inspired air (e.g., heat-moisture exchanger, heated humidifier)
2. A thermometer or sensing device to measure the temperature of inspired air
3. An apnea or low-pressure alarm that indicates leaks or that the patient is not ventilating adequately*
4. A nebulizer line to power a micronebulizer for delivery of aerosolized medications*
5. A volume-measuring device to determine the patient's exhaled volume*
6. Bacterial filters to filter gas administered to the patient and exhaled by the patient
7. A pressure gauge to measure pressures in the upper airway*
8. In-line suction catheter

*Usually built into the ventilator.

Volume Displacement Designs

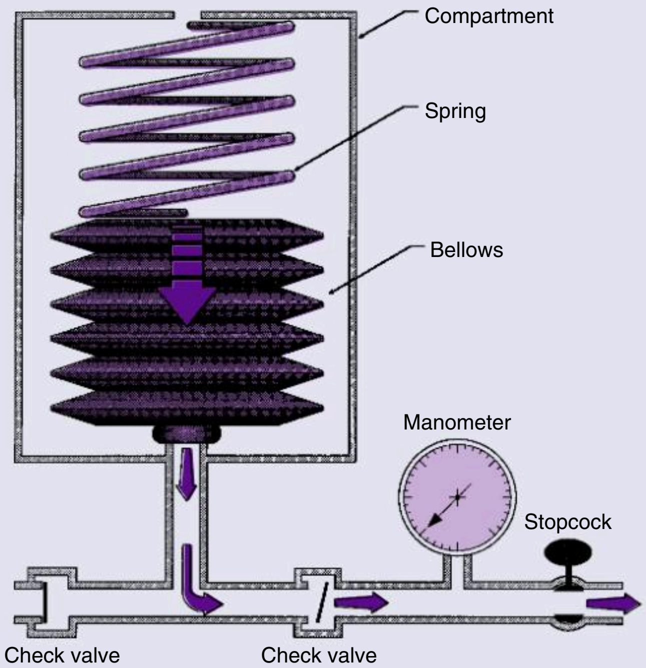
Volume displacement devices include bellows, pistons, concertina bags, and bag-in-a-chamber systems.[7,8] Box 2.5 provides a brief

BOX 2.5 Examples of Volume Displacement Devices

Spring-Loaded Bellows

In a spring-loaded bellows model, an adjustable spring atop a bellows applies a force per unit area, or pressure (P = Force/Area). Tightening of the spring creates greater force and therefore greater pressure. The bellows contains preblended gas (air and oxygen), which is administered to the patient. The Servo 900C ventilator is an example of a ventilator that uses a spring-loaded bellows (pressure of up to 120 cm H_2O). Although these devices are no longer manufactured, it is worth noting because of their importance in the development of modern mechanical ventilators.

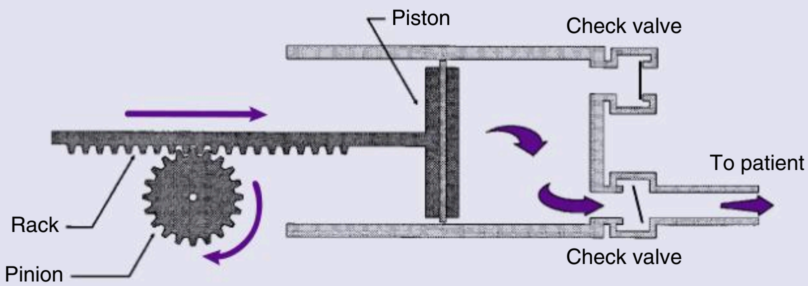
A spring-loaded bellows mechanism.



Linear Drive Piston

In a linear drive device, an electrical motor is connected by a special gearing mechanism to a piston rod or arm. The rod moves the piston forward inside a cylinder housing in a linear fashion at a constant rate. Some high-frequency ventilators use linear or direct drive pistons. Incorporating a rolling seal or using low-resistance materials has helped eliminate the friction that occurred with early piston/cylinder designs. The Puritan Bennett 760 ventilator is an example of a linear drive piston device.

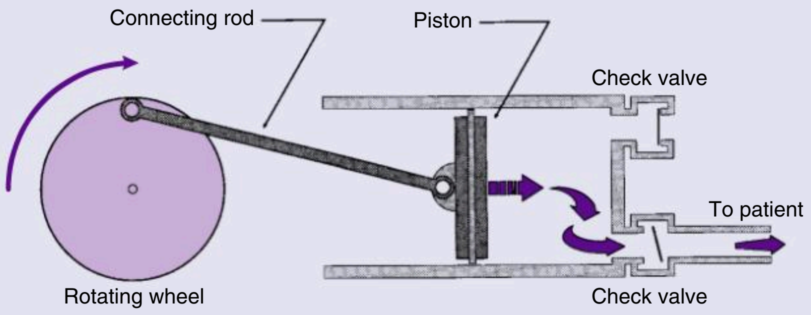
A linear drive piston.



Rotary Drive Piston

This type of drive mechanism is called a *rotary drive,* a *nonlinear drive,* or an *eccentric drive* piston. An electric motor rotates a drive wheel. The resulting flow pattern is slow at the beginning of inspiration, achieves highest speed at midinspiration, and tapers off at end-inspiration. This pattern is called a *sine* (sinusoidal) *waveform.* The Puritan Bennett Companion 2801 ventilator, which is used in home care, has this type of piston.

A rotary drive piston.



description of the principle of operation for each of these devices and examples of ventilators that use these mechanisms.

Volume Flow-Control Valves

Current ICU ventilators use flow-control valves to regulate gas flow to the patient. These flow-control valves operate by opening and closing either completely or in small increments. These valves, which are driven by various motor-based mechanisms, have a rapid response time and great flexibility in flow control. Flow-control valves include proportional solenoid valves and digital valves with on/off configurations.

A proportional solenoid valve can be designed with various configurations to modify gas flow. A typical valve incorporates a gate or plunger, a valve seat, an electromagnet, a diaphragm, a spring, and two electrical contacts (Fig. 2.10). Electric current flows through the electromagnet and creates a magnetic field, which pulls the plunger and opens the valve. The amount of current flowing through the electromagnet influences the strength of the magnetic field; the strength of the field determines the position of the plunger, or *armature.* The design of the plunger can vary from ventilator to ventilator.

Solenoids can be controlled by electrical timers or microprocessors, manual operation, and pressure. With electrical timers and microprocessors, electric current passes to the electromagnet and opens the valve. Manual operation closes a switch, sending a current to the electromagnet and opening the valve. Pressure changes generated by a patient's inspiratory effort can cause a diaphragm to move, closing an electrical contact and opening or closing the valve.[7,8] Examples of ventilators with this type of valve include Medtronic PB 840/980, the Hamilton G5 (Hamilton Medical), the Dräger Evita Infinity V500, and the Servo-i (Getinge).

In the digital on/off valve configuration, several valves operate together. Each valve is either open or closed (Fig. 2.11). A particular valve produces a certain flow by controlling the opening and closing of a specifically sized orifice. The amount of flow varies depending on which valves are open. The Infant Star ventilator used this type of valve configuration.

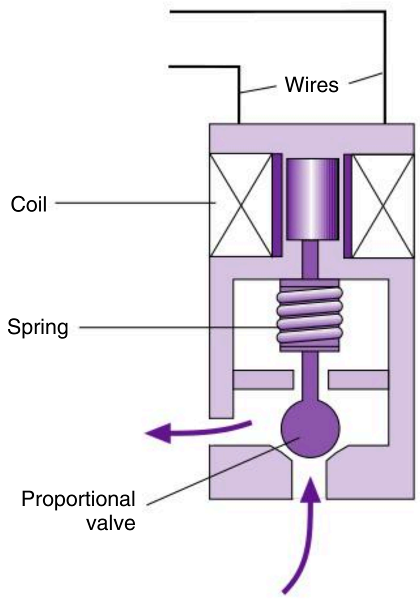


Fig. 2.10 Proportional solenoid valve, a type of flow control valve. In this design an electric current, which can be controlled, flows through the coil, creating a magnetic field. The strength of the magnetic field causes the armature to assume a specified position. With the armature and valve poppet physically connected, this assembly is the only moving part. Coil and armature designs vary, as do strategies for fixing the position of the poppet. (Redrawn from Sanborn WG: Microprocessor-based mechanical ventilation, *Respir Care* 38:72—109, 1993.)

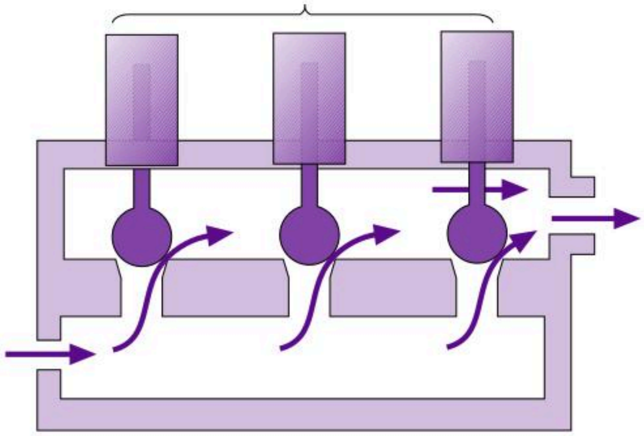


Fig. 2.11 Digital on/off valve, another type of pneumatic flow control valve. With each valve controlling a critical orifice and thus a specified flow, the number of discrete flow steps (including zero) becomes 2^n (where n = number of valves). (Redrawn from Sanborn WG: Microprocessor-based mechanical ventilation, *Respir Care* 38:72–109, 1993.)

SUMMARY

- The major components of a mechanical ventilator include a high-pressure gas source, a control panel (user interface) to establish the pressure and pattern of gas flow delivered by the machine, and a control system that interprets the operator's settings and produces and regulates the desired output.
- Ventilator power sources may operate on electrical or pneumatic (gas) power. Electrically powered ventilators may rely on an alternating current wall outlet or a direct current source, such as a battery. Pneumatically powered ventilators are classified as pneumatic ventilators and fluidic ventilators. Pneumatically powered, microprocessor-controlled ventilators use compressed gas input power to drive inspiration and use electrical power to control the breath characteristics.
- With positive pressure ventilators, gas flows into the lung because the ventilator establishes a pressure gradient by generating a positive pressure at the airway opening.
- Negative pressure ventilators create a transairway pressure gradient between the airway opening and the alveoli by generating a negative pressure at the body surface. This negative pressure is transmitted to the pleural space and then to the alveoli. The ventilator's control circuit, or decision-making system, uses mechanical or electrical devices, electronics, pneumatics, fluidics, or a combination of these to regulate ventilator function.
- The control panel, or user interface, has various knobs or touch pads for setting components, such as tidal volume, rate, inspiratory time, alarms, and F_{IO_2}.
- With an open-loop system, the ventilator cannot be programmed to respond to changing conditions. In contrast, a closed-loop system is often described as an "intelligent" system because the ventilator can be programmed to compare the set control variable with the measured control variable.
- The major components of a patient circuit include the main inspiratory line, which connects the ventilator output to the patient's airway adapter or connector; an adapter that connects the main inspiratory line to the patient's airway; an expiratory line that delivers expired gas from the patient to the exhalation valve; and an expiratory valve that allows the release of exhaled gas from the expiratory line into the room air.
- The internal hardware that accomplishes the conversion of electrical or pneumatic energy required to perform these mechanical operations is called the *power transmission and conversion system*. It consists of a drive mechanism and an output control mechanism.
- The ventilator's drive mechanism is a mechanical device that produces gas flow to the patient. These are generally classified as volume displacement and flow devices. The output control consists of one or more valves that determine the gas flow to the patient.
- Some ventilators use volume displacement devices, such as bellows, pistons, concertina bags, and bag-in-a-chamber systems. Common examples include spring-loaded bellows, linear-drive pistons, and rotary-drive pistons.

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

1. Name a commercially available ventilator that is entirely pneumatically powered.
2. Give an example of an electrically powered ventilator.
3. What type of ventilator delivers pressures below ambient pressure on the body surface and mimics the physiology of normal breathing?
4. Explain the operation of an externally mounted exhalation valve.
5. What volume displacement device creates a sine waveform for gas flow?
6. A Dräger Evita Infinity V500 ventilator is set to deliver a minute ventilation of 5 L/min. The patient breathes six times in 1 minute and receives a mandatory breath of 500 mL with each breath. The ventilator detects the difference between the actual and the set minute ventilation and adds four more breaths (500 mL each) to make up the difference. Which of the following best describes this type of ventilator?
   A. Closed loop
   B. Open loop
7. The controls set by the ventilator operator are considered part of the:
   A. Pneumatic drive circuit
   B. Electrical motor
   C. User interface
   D. Pneumatic circuit
8. The gas-conducting tubes that carry gas from the ventilator to the patient are referred to as the:
   A. Internal pneumatic circuit
   B. Control circuit

C. Control scheme
D. Patient circuit

9. A ventilator in which the gas that enters the patient's lungs is also the gas that powers the unit is referred to as a:
A. Direct drive ventilator
B. Single-circuit ventilator
C. Double-circuit ventilator
D. Single-power source ventilator

10. In a spring-loaded bellows volume-delivery device, the amount of pressure is determined by the:
A. Location of the bellows
B. Volume setting on the ventilator
C. Tightness of the spring
D. Electrical power provided to the spring

11. Which of the following is an example of a flow control valve?
A. Linear piston
B. Spring-loaded bellows
C. Solenoid
D. Rotary drive piston

12. An electric current flows through an electromagnet and creates a magnetic field, pulling a plunger and opening a valve. This description best fits which of the following devices?
A. Proportional solenoid valve
B. Eccentric valve piston
C. Digital valve
D. Linear drive piston

References

1. Chatburn RL: Classification of mechanical ventilators, *Respir Care* 37:1009—1025, 1992.
2. Chatburn RL: Classification of ventilator modes: update and proposal for implementation, *Respir Care* 52(3):301—323, 2007.
3. Op't Holt TB: Introduction to ventilators. In Cairo JM, editor: *Mosby's respiratory care equipment*, ed 11, St. Louis, MO, 2022, Elsevier.
4. Mushin WW, Rendell-Baker L, Thompson PW, et al.: *Automatic ventilation of the lungs*, Philadelphia, PA, 1980, FA Davis.
5. Tehrani FT: Automatic control of mechanical ventilation. Part 1: theory and history of technology, *J Clin Monit Comput* 22:417—424, 2008.
6. Chatburn RL: Computer control of mechanical ventilation, *Respir Care* 49:507—517, 2004.
7. Sanborn WG: Microprocessor-based mechanical ventilation, *Respir Care* 38(1):72—109, 1993.
8. Dupuis Y: *Ventilators: theory and clinical application*, ed 2, St. Louis, MO, 1992, Mosby.

CHAPTER 3

How a Breath Is Delivered

OUTLINE

KEY TERMS

- Assisted breath
- Autotrigger
- Baseline variable
- Continuous positive airway pressure
- Control mode
- Control variable
- Cycle variable
- Equation of motion
- Flow-controlled ventilation
- Flow cycling
- Flow limited
- Flow triggering
- Frequency control
- Inspiratory pause
- Limit variable
- Mandatory breath
- Mode
- Negative end-expiratory pressure
- Patient triggering
- Phase variable
- Plateau pressure
- Positive end-expiratory pressure
- Pressure-controlled ventilation
- Pressure cycling
- Pressure limiting
- Pressure support
- Pressure triggering
- Rate control
- Spontaneous breaths
- Time cycled
- Time triggering
- Trigger variable
- Triggering mechanism
- Volume-controlled ventilation
- Volume cycled
- Volume limiting
- Volume triggering

LEARNING OBJECTIVES

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

1. Write the equation of motion and define each term in the equation.
2. Give two other names for pressure ventilation and volume ventilation.
3. Compare pressure, volume, and flow delivery in volume-controlled breaths and pressure-controlled breaths.
4. Name the two most commonly used patient-trigger variables.
5. Identify the patient-trigger variable that requires the least work of breathing for a patient receiving mechanical ventilation.
6. Explain the effect on the volume delivered and the inspiratory time if a ventilator reaches the set maximum pressure limit during volume ventilation.
7. Recognize the effects of a critical ventilator circuit leak on pressure readings and volume measurements.
8. Define the effects of inflation hold on inspiratory time.
9. Give an example of a current ventilator that provides negative pressure during part of the expiratory phase.
10. On the basis of the description of a pressure-time curve, identify a clinical situation in which expiratory resistance is increased.
11. Describe two methods of applying continuous pressure to the airways that can be used to improve oxygenation in patients with refractory hypoxemia.

Selecting the most effective mode of ventilation to use after it has been decided that a patient will require mechanical ventilation requires understanding of the functional capabilities of a ventilator. Answers to several questions provide a framework to explain the method by which a ventilator accomplishes delivery of a breath: (1) What is the source of energy used to deliver the breath (i.e., is the energy provided by the ventilator or by the patient)? (2) What factor does the ventilator control to deliver the breath (e.g., pressure, volume, flow, or time)? (3) How are the phases of a breath accomplished (i.e., what begins a breath, how is it delivered, and what ends the breath)? (4) Is the breath mandatory, assisted, or spontaneous? All of these factors determine the mode of ventilation, and each concept is reviewed in this chapter.

BASIC MODEL OF VENTILATION IN THE LUNG DURING INSPIRATION

One approach that can be used to understand the mechanics of breathing during mechanical ventilation involves using a mathematical model based on the **equation of motion.** This equation describes the relationships among pressure, volume, and flow during a spontaneous or mechanical breath.[1-3] The equation includes three terms, which were previously defined in Chapter 1, namely P_{TR}, or transrespiratory pressure; P_E, or elastic recoil pressure; and P_R, or flow resistance pressure. Fig. 3.1 provides a graphic representation of each of these pressures.[4]

Box 3.1 summarizes the factors that influence the movement of air into lungs. Notice that the left side of the equation of motion shown in Box 3.1 represents the transrespiratory pressure (P_{TR}), which is the energy (i.e., pressure) required to establish a pressure gradient to move gas into the lungs. The P_{TR} can be achieved by contraction of the respiratory muscles (P_{mus}) during a spontaneous breath or generated by the ventilator (P_{vent}) during a mechanical breath. The right side of the equation shows factors that influence the impedance that must be overcome to move air into the lungs. Elastic recoil pressure (P_E) is the elastic load offered by the lungs and chest wall and the flow resistance pressure or airway resistance (P_R) produced as gas flows through the conducting airways. Note that elastance can be defined as the ratio of pressure change to volume change (i.e., elastance is the inverse of compliance). Flow resistance is defined as the ratio of pressure change to the flow of gas into the lungs. As described in Box 3.1, the transrespiratory pressure therefore equals the pressure that must be generated to overcome the elastance (or compliance) of the lungs and chest wall plus the flow resistance required to move gas into the lungs. During a spontaneous breath, the inspiratory muscles (i.e., diaphragm and external intercostal muscles) contract, causing enlargement of the lungs and thorax. As discussed in Chapter 1, this increase in lung volume results in a decrease (more

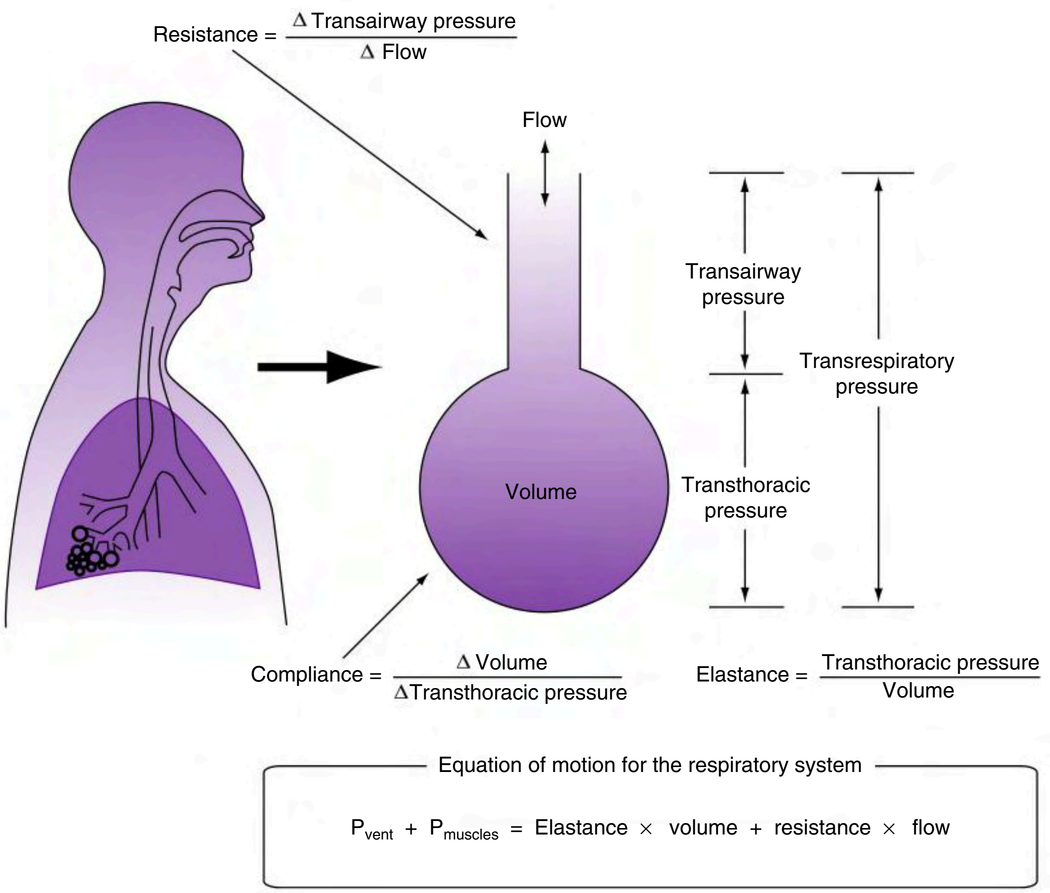


Fig. 3.1 Equation of motion model. The respiratory system can be visualized as a conductive tube connected to an elastic compartment (balloon). Pressure, volume, and flow are variables and functions of time. Resistance and compliance are constants. Transthoracic pressure is the pressure difference between the alveolar space (P_{alv}), or lung, and the body surface (P_{bs}). (See text for further explanation.) (From Kacmarek RM, Stoller JK, Heuer AJ, editors: *Egan's fundamentals of respiratory care*, ed 12, St. Louis, MO, 2021, Elsevier.)

BOX 3.1 Equation of Motion

$$P_{mus} + P_{vent} = P_E + P_R$$

where Muscle pressure + Ventilator pressure = Elastic recoil pressure + Flow resistance pressure.

If one considers that:

$$\text{Elastic recoil pressure} = \text{Elastance} \times \text{Volume} = \text{Volume/Compliance } (V/C), \text{ and}$$
$$\text{Flow resistance pressure} = \text{Resistance} \times \text{Flow} = \left(R_{aw} \times \dot{V}\right)$$

Then the equation can be rewritten as follows:

$$P_{mus} + P_{vent} = V/C + \left(R_{aw} \times \dot{V}\right)$$

P_{mus} is the pressure generated by the respiratory muscles *(muscle pressure).* If these muscles are inactive, $P_{mus} = 0$ cm H_2O, then the ventilator must provide the pressure required to achieve an inspiration.

P_{vent}, or more specifically P_{TR}, is the pressure read on the ventilator gauge (manometer) during inspiration with positive pressure ventilation (i.e., the ventilator gauge pressure). V is the volume delivered, C is respiratory system compliance, V/C is the elastic recoil pressure, R_{aw} is airway resistance, and $\dot{V}$ is the gas flow during inspiration ($R_{aw} \times \dot{V}$ = Flow resistance).

Because $P_{alv} = V/C$ and $P_{TA} = R_{aw} \times \dot{V}$, substituting in the above equation results in:

$$P_{mus} + P_{TR} = P_{alv} + P_{TA}$$

where P_{alv} is the alveolar pressure and P_{TA} is the transairway pressure (peak pressure minus plateau pressure [PIP − P_{plat}]) (see Chapter 1 for further explanation of abbreviations).

negative) in intrapleural pressure and an increase in transrespiratory pressure ($P_{TR} = P_{alv} - P_{pl}$). The pressure gradient established by contraction of the inspiratory muscles (i.e., muscle pressure [P_{mus}]) during a spontaneous breath therefore provides the energy to overcome the impedance (lung and chest wall elastance + airway resistance) to move air into the lungs.

If the respiratory muscles are inactive, a mechanical ventilator can be used to provide the energy required to establish the pressure gradient required to move gas into the lungs by generating a positive pressure (P_{vent}) at the airway opening. The ventilator pressure (P_{vent}) generated during inspiration therefore represents the transrespiratory pressure (P_{TR}) required to overcome the impedance offered by the respiratory system (i.e., the ventilator performs all of the work required to move air into the lungs).

It is important to recognize that the two examples cited previously represent the extremes of a continuum. During spontaneous ventilation, the patient provides the energy required to pull gas into the lungs, whereas in the latter example the ventilator provides all of the energy to push the gas into the patient's lungs. Keep in mind that an infinite number of combinations of P_{mus} and P_{vent} can be used to achieve the total force required during assisted ventilation.[5]

FACTORS CONTROLLED AND MEASURED DURING INSPIRATION

Delivery of an inspiratory volume is perhaps the single most important function a ventilator accomplishes. Two factors determine the way the inspiratory volume is delivered: the structural design of the ventilator and the ventilator **mode** set by the clinician. The clinician sets the mode by selecting either a predetermined pressure or volume as the target variable (Box 3.2).

The primary variable the ventilator adjusts to achieve inspiration is called the **control variable** (Key Point 3.1).[6] As the equation of motion shows, the ventilator can control four variables: pressure, volume, flow, and time. It is important to recognize that the ventilator can control only one variable at a time. Thus, a ventilator can operate as a pressure controller, a volume controller, a flow controller, or a time controller (Box 3.3).

BOX 3.2 Common Methods of Delivering Inspiration

Pressure-Controlled Ventilation

The clinician sets a pressure for delivery to the patient. Pressure-controlled ventilation is also called:

- Pressure-targeted ventilation
- Pressure ventilation

Volume-Controlled Ventilation

The clinician sets a volume for delivery to the patient. Volume-controlled ventilation is also called:

- Volume-targeted ventilation
- Volume ventilation

***Key Point* 3.1** The primary variable that the ventilator adjusts to produce inspiration is the control variable. The most commonly used control variables are pressure and volume.

BOX 3.3 Ventilator Control Functions During Inspiration

- *Pressure controller:* The ventilator maintains the same pressure waveform at the mouth regardless of changes in lung characteristics.
- *Volume controller:* Ventilator volume delivery and volume waveform remain constant and are not affected by changes in lung characteristics. Volume is measured.*
- *Flow controller:* Ventilator volume delivery and flow waveform remain constant and are not affected by changes in lung characteristics. Flow is measured.*
- *Time controller:* Pressure, volume, and flow curves can change as lung characteristics change. Time remains constant.

*Volume delivery by current-generation mechanical ventilators is a product of measured flow and inspiratory time. The ventilator essentially controls the flow delivered to the patient and calculates volume delivery based on the rate of flow and the time allowed for flow. Basically, the same effect is achieved by controlling either the volume delivered or flow over time.

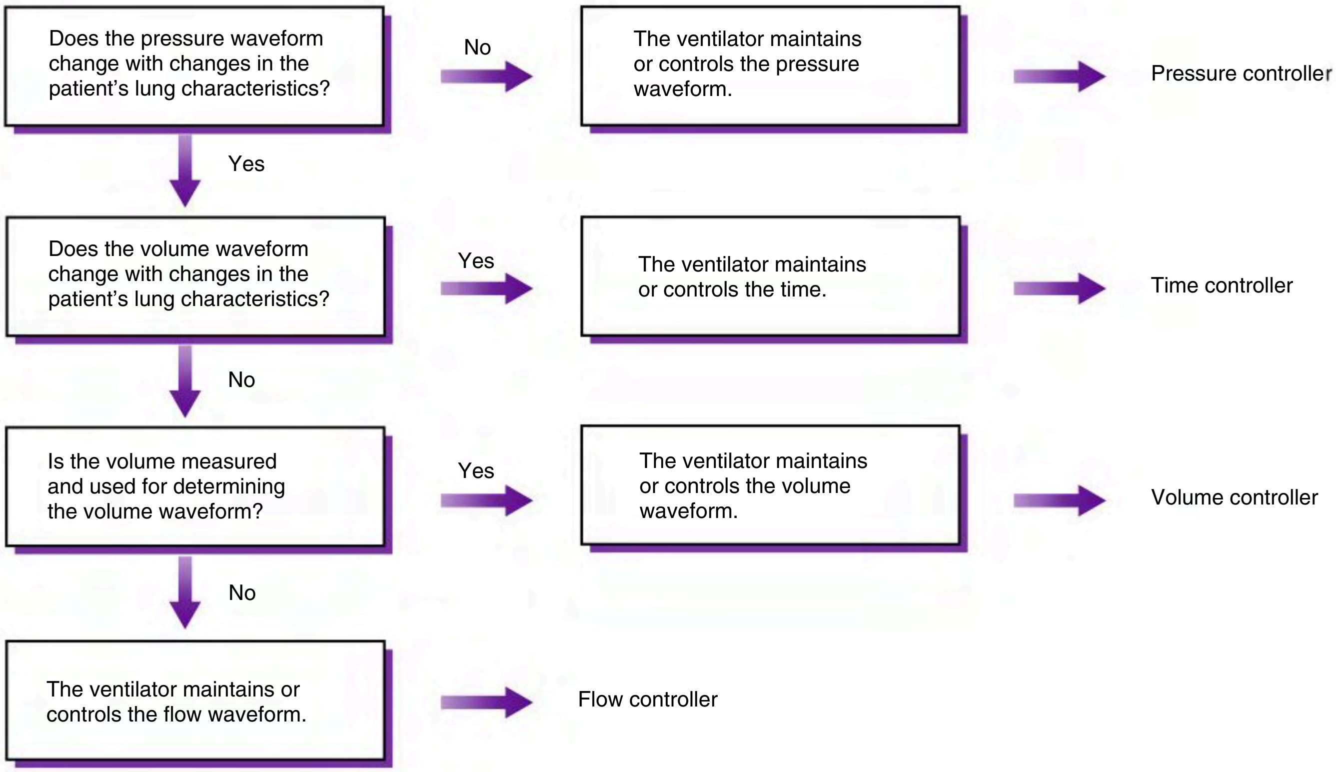


Fig. 3.2 Defining a breath based on how the ventilator maintains the inspiratory waveforms. (Modified from Chatburn RL: Classification of mechanical ventilators, *Respir Care* 37:1009—1025, 1992.)

Pressure-Controlled Breathing

When the ventilator maintains the pressure waveform in a specific pattern, the delivered breath is described as *pressure controlled*. With **pressure-controlled ventilation,** the pressure waveform is unaffected by changes in lung characteristics. The volume and flow waveforms will vary with changes in the compliance and resistance characteristics of the patient's respiratory system.

Volume-Controlled Breathing

When a ventilator maintains the volume waveform in a specific pattern, the delivered breath is *volume controlled*. During **volume-controlled ventilation,** the volume and flow waveforms remain unchanged, but the pressure waveform varies with changes in lung characteristics.

Flow-Controlled Breathing

When the ventilator controls flow, the flow and therefore volume waveforms remain unchanged but the pressure waveform changes with alterations in the patient's lung characteristics. **Flow-controlled ventilation** can be achieved directly by a device as simple as a flowmeter or by a more complex mechanism, such as a solenoid valve (see Chapter 2).[6] Notice that any breath that has a set flow waveform also has a set volume waveform and vice versa. Thus when the clinician selects a flow waveform, the volume waveform is automatically established (Flow = Volume change/Time; Volume = Flow × Time). In practical terms, clinicians typically are primarily interested in volume and pressure delivery rather than the contour of the flow waveform.

Time-Controlled Breathing

When the pressure, volume, and flow waveforms are affected by changes in lung characteristics, the ventilator can control the ventilatory cycle and is described as delivering a breath as **time-controlled ventilation.** High-frequency jet ventilators and oscillators control inspiratory and expiratory times and are therefore examples of mechanical ventilators that can be classified as time-controlled ventilators.

OVERVIEW OF INSPIRATORY WAVEFORM CONTROL

Fig. 3.2 provides an algorithm to identify the various types of breaths that can be delivered by mechanical ventilators. Fig. 3.3 shows the waveforms for pressure- and volume-controlled ventilation, and Box 3.4 lists basic points that can help simplify evaluation of a breath during inspiration.[7]

The airway pressure waveforms shown in Fig. 3.3 illustrate what the clinician would see on the ventilator graphic display as gas is delivered. The ventilator typically measures variables in one of three places: (1) at the upper, or proximal, airway, where the patient is connected to the ventilator; (2) internally, near the point where the main circuit lines connect to the ventilator; or (3) near the exhalation valve.*

*Many ventilators have pressure-measuring devices placed on both the inspiratory and expiratory sides of a ventilator circuit.

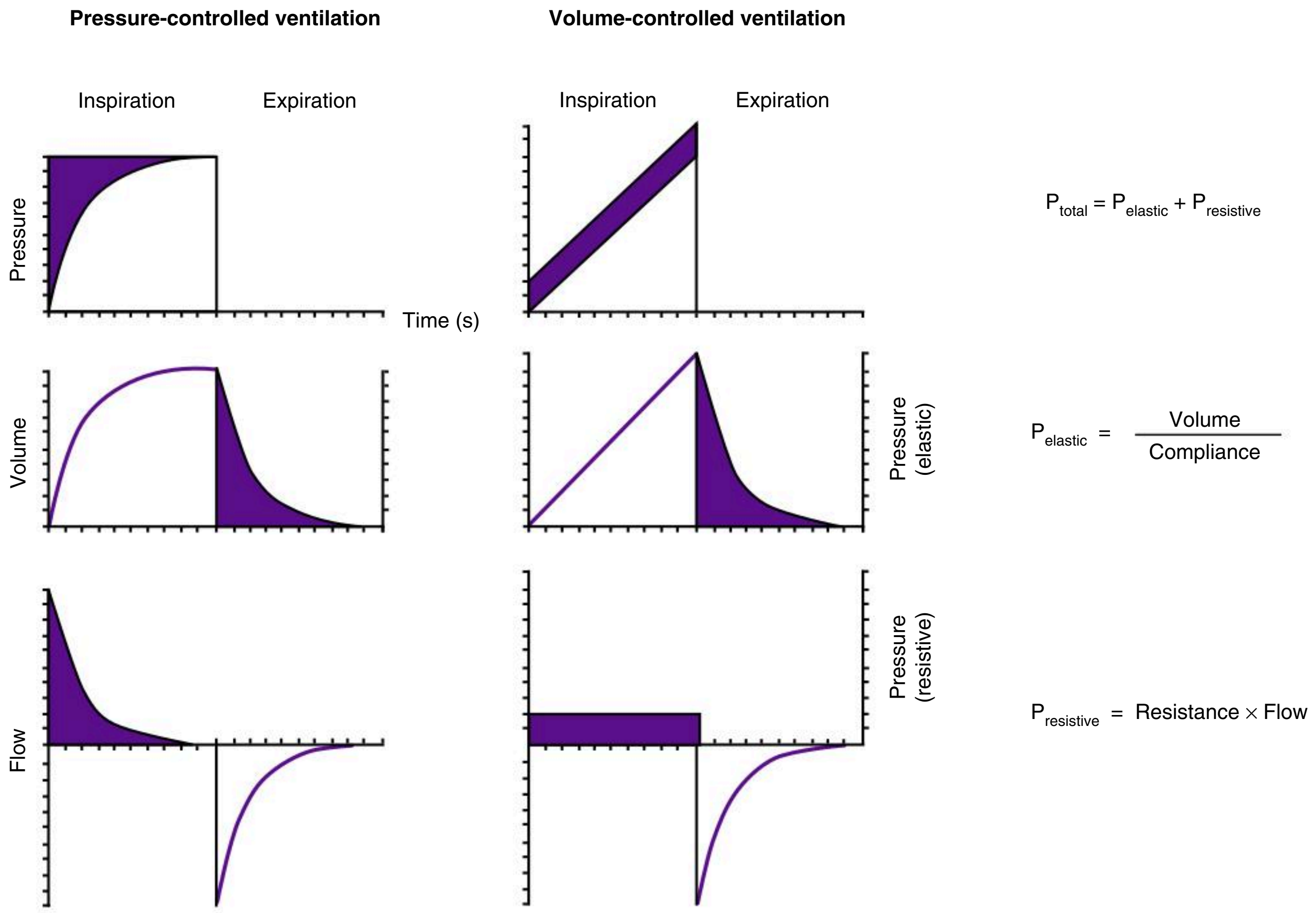


Fig. 3.3 Characteristic waveforms for pressure-controlled ventilation and volume-controlled ventilation. Note that the volume waveform has the same shape as the transthoracic (lung pressure) waveform (i.e., pressure caused by the elastic recoil [compliance] of the lung). The flow waveform has the same shape as the transairway pressure waveform (peak inspiratory pressure minus plateau pressure [PIP − P_{plat}]) (shaded area of pressure−time waveform). The *shaded areas* represent pressures caused by resistance, and the *open areas* represent pressure caused by elastic recoil. (From Kacmarek RM, Stoller JK, Heuer AJ, editors: *Egan's fundamentals of respiratory care,* ed 12, St. Louis, MO, 2021, Elsevier.)

BOX 3.4 Basic Points for Evaluating a Breath During Inspiration

1. Inspiration is commonly described as *pressure controlled* or *volume controlled.* Although both *flow-* and *time-controlled* ventilation have been defined, they are not typically used.
2. *Pressure-controlled* inspiration maintains the same pattern of pressure at the mouth regardless of changes in lung condition.
3. *Volume-controlled* inspiration maintains the same pattern of volume at the mouth regardless of changes in lung condition and also maintains the same flow waveform.
4. The pressure, volume, and flow waveforms produced at the mouth usually take one of four shapes:
   a. Rectangular (also called *square* or *constant*)
   b. Exponential (may be increasing [rising] or decreasing [decaying])
   c. Sinusoidal (also called *sine wave*)
   d. Ramp (available as ascending or descending [decelerating] ramp)

Microprocessor-controlled ventilators have the capability of displaying these waveforms as scalars (a variable graphed relative to time) and loops on the ventilator's graphic display.[6] As discussed in Chapter 9, this graphic information is an important tool that can be used for the management of the patient-ventilator interaction.

PHASES OF A BREATH AND PHASE VARIABLES

The following section describes the phases of a breath and the variable that controls each portion of the breath (i.e., the **phase variable**). As summarized in Box 3.5, the phase variable represents the signal measured by the ventilator that is associated with a specific aspect of the breath. The **trigger variable** begins inspiration. The **limit variable** limits the value of pressure, volume, flow, or time during inspiration. It is important to recognize that the limit variable does not end inspiration. The **cycle variable** ends inspiration. The **baseline variable** establishes the baseline during expiration before inspiration is triggered. Pressure is usually identified as the baseline variable.

Beginning of Inspiration: The Trigger Variable

The mechanism the ventilator uses to begin inspiration is the **triggering mechanism** (trigger variable). The ventilator can initiate a breath after a set time (**time triggering**), or the patient can trigger the machine (**patient triggering**) based on pressure, flow, or volume changes. Pressure and flow triggering are the most common triggering variables, but **volume triggering** and neural triggering from the diaphragm output can be used. Most ventilators also allow the operator to manually trigger a breath (Key Point 3.2).

Time Triggering

With time triggering, the ventilator delivers a mandatory breath by beginning inspiration after a set time has elapsed. (NOTE: The set time is based on the total cycle time [TCT], which is the sum of inspiratory time [T_I] and expiratory time [T_E], or $TCT = T_I + T_E$). In other words, the number of mandatory breaths delivered by the ventilator is based on the length of the TCT. For example, if the breathing rate is set at 20 breaths per minute, the ventilator triggers inspiration after 3 seconds elapses (60 s/min divided by 20 breaths/min = 3 seconds).

In the past, time-triggered ventilation did not allow a patient to initiate a breath (i.e., the ventilator was "insensitive" to the patient's effort to breathe). Consequently, when the **control mode** setting was selected on early ventilators such as the first Emerson Post-Op, the machine automatically controlled the number of breaths delivered to the patient.

BOX 3.5 Phase Variables

A *phase variable* begins, sustains, ends, and determines the characteristics of the expiratory portion of each breath. Four phase variables are typically described:

1. The trigger variable begins inspiration.
2. The limit variable limits the pressure, volume, flow, or time during inspiration but does not end the breath.
3. The cycle variable ends the inspiratory phase and begins exhalation.
4. The baseline variable is the end-expiratory baseline (usually pressure) before a breath is triggered.

Key Point 3.2 The trigger variable initiates inspiratory flow from the ventilator.

Ventilators are no longer used in this manner. Conscious patients are almost never "locked out," and they can take a breath when they need it. The clinician sets up time triggering with the **rate control** (or **frequency control**), which may be a touch pad or a knob. Sometimes clinicians may say that a patient "is being controlled" or "is in the control mode" to describe an individual who is apneic or *sedated* or paralyzed and makes no effort to breathe (Fig. 3.4). It should be noted, however, that the ventilator should be set so that it will be sensitive to the patient's inspiratory effort when the person is no longer apneic or paralyzed.

Patient Triggering

In cases in which a patient attempts to breathe spontaneously during mechanical ventilation, a ventilator must be able to measure the patient's effort to breathe. When the ventilator detects changes in pressure, flow, or volume, a patient-triggered breath occurs. Pressure and flow are common patient-triggering mechanisms (e.g., inspiration begins if a negative airway opening pressure or change in flow is detected). Fig. 3.5 illustrates a breath triggered by the patient making an inspiratory effort (i.e., the patient's inspiratory effort can be identified as the pressure deflection below baseline that occurs before initiation of the mechanical breath). To enable patient triggering, the clinician must specify the sensitivity setting, also called the *patient effort* (or *patient-triggering*) *control.* This setting determines the pressure or flow change required to trigger the ventilator. The less pressure or flow change required to trigger a breath, the more sensitive the machine is to the patient's effort. For example, the ventilator is more sensitive to patient effort at a setting of -0.5 cm H_2O than at a setting of -1 cm H_2O. Sensing devices are usually located inside the ventilator near the output side of the system; however, in some systems, pressure or flow is measured at the proximal airway.

The sensitivity level for **pressure triggering** is usually set at about -1 cm H_2O. The clinician must set the sensitivity level to fit the patient's needs. If it is set incorrectly, the ventilator may not be sensitive enough to the patient's effort, and the patient will have to work too hard to trigger the breath (Fig. 3.6). Conversely, if it is too sensitive, the ventilator can **autotrigger** (i.e., the ventilator triggers a breath without the patient trying to initiate a breath) (Case Study 3.1).

Flow triggering occurs when the ventilator detects a reduction in flow through the patient circuit during exhalation. To enable flow triggering, the clinician must set an appropriate flow that must be sensed by the ventilator to trigger the next breath. As an example, a ventilator has a baseline flow of 6 L/min. This allows 6 L/min of gas to flow through the patient circuit during the last part of exhalation. The sensors measure a flow of 6 L/min leaving the

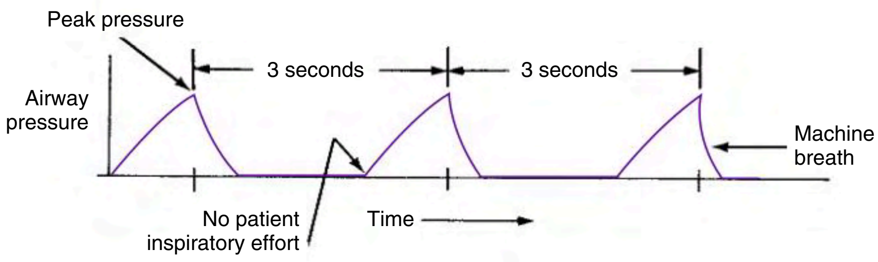


Fig. 3.4 Controlled ventilation pressure curve. Patient effort does not trigger a mechanical breath; rather, inspiration occurs at equal, timed intervals.

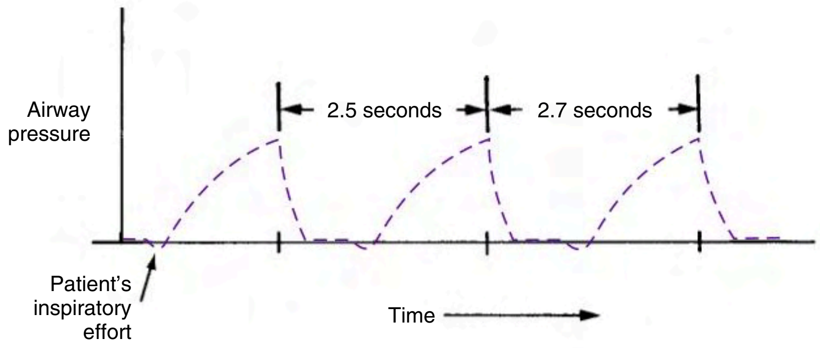


Fig. 3.5 Assist pressure curve. Patient effort (negative pressure deflection from baseline) occurs before each machine breath. Breaths may not occur at equal, timed intervals.

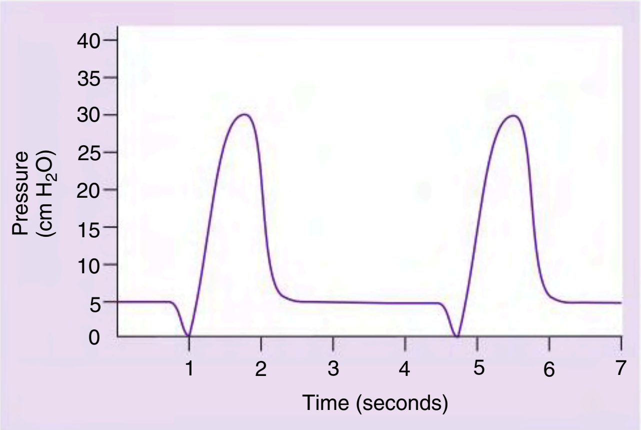


Fig. 3.6 Airway pressure curve during assist ventilation with 5 cm H_2O of positive end-expiratory pressure (baseline), showing a deflection of the pressure curve to 0 cm H_2O before each machine breath is delivered. The machine is not sensitive enough to the patient's effort.

Case Study 3.1

Patient Triggering

Problem 1: A patient is receiving volume-controlled ventilation. Whenever the patient makes an inspiratory effort, the pressure indicator shows a pressure of −5 cm H_2O below baseline before the ventilator triggers into inspiration. What does this indicate?

Problem 2: A patient appears to be in distress while receiving volume-controlled ventilation. The ventilator is cycling rapidly from breath to breath. The actual rate is much faster than the set rate. No discernible deflection of the pressure indicator occurs at the beginning of inspiration. The ventilator panel indicates that every breath is an assisted, or patient-triggered, breath. What does this indicate?

ventilator and 6 L/min returning to the ventilator. If the flow trigger is set at 2 L/min, the ventilator will begin an assisted breath when it detects a decrease in flow of 2 L/min from the baseline (i.e., 4 L/min returning to the ventilator [Fig. 3.7]).

When set properly, flow triggering has been shown to require less work of breathing than pressure triggering. Many microprocessor-controlled ventilators (e.g., Servo-i, Hamilton G5, Medtronics Puritan Bennett 840/980) offer flow triggering as an option.

Volume triggering occurs when the ventilator detects a small drop in volume in the patient circuit during exhalation. The machine interprets this decrease in volume as a patient effort and begins inspiration. Neural triggering is a relatively newer triggering option that allows the ventilator to initiate a breath when electrical activity of the diaphragm is sensed. **Neurally adjusted ventilatory assist** (**NAVA**) is available on the Getinge Servo ventilators and is discussed in greater detail in Chapter 23.

As mentioned previously, manual triggering is also available. With manual triggering, the operator can initiate a ventilator breath by pressing a button or touch pad labeled "Manual" breath or "Start" breath. When this control is activated, the ventilator delivers a breath according to the set variables.

It is important to recognize that patient triggering can be quite effective when a patient begins to breathe spontaneously, but occasionally the patient may experience an apneic episode. For this reason, a respiratory rate is set with the rate control to guarantee a minimum number of breaths per minute (Fig. 3.8). Each breath is either patient triggered or time triggered, depending on which occurs first. Although the rate control determines the minimum number of mechanical breaths delivered, the patient has the option of breathing at a faster rate. Clinicians often refer to this as the *assist-control mode.* (NOTE: The clinician must always make sure the ventilator is sensitive to the patient's efforts [Box 3.6].)

The Limit Variable During Inspiration

Inspiration is timed from the beginning of inspiratory flow to the beginning of expiratory flow. As mentioned previously, the ventilator can determine the waveform for pressure, volume, flow, or time during inspiration. However, it can also limit these variables. For example, during volume-controlled ventilation of an apneic patient, the clinician sets a specific volume that the ventilator will deliver. In general, the volume delivered cannot exceed that amount; it may be for some reason less than desired, but it cannot be more.

A limit variable is the maximum value that a variable (pressure, volume, flow, or time) can attain. It is important to emphasize, however, that reaching the set limit variable *does not* end inspiration. As an example, a ventilator is set to deliver a maximum pressure of 25 cm H_2O and the inspiratory time is set at 2 seconds.

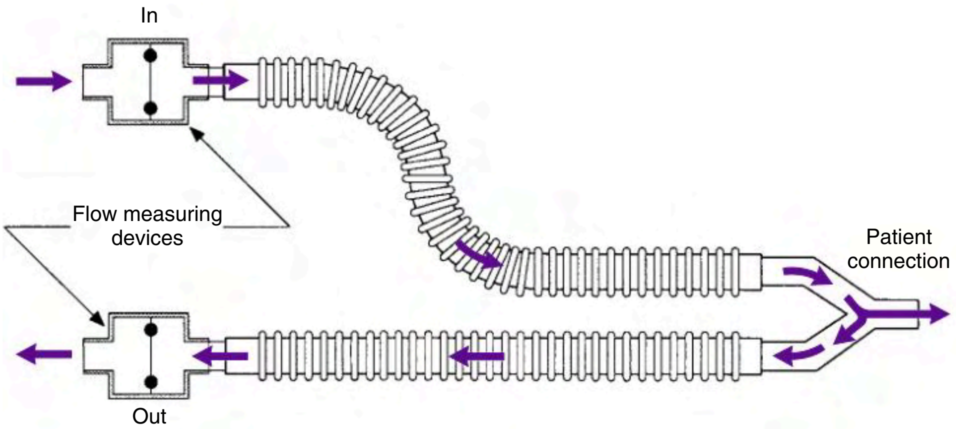


Fig. 3.7 Schematic drawing of the essential features of flow triggering. Triggering occurs when the patient inspires from the circuit and increases the difference between flow from the ventilator (inspiratory side, *in*) and flow back to the exhalation valve (expiratory side, *out*). (From Dupuis Y: *Ventilators: theory and clinical application,* ed 2, St. Louis, MO, 1992, Mosby.)

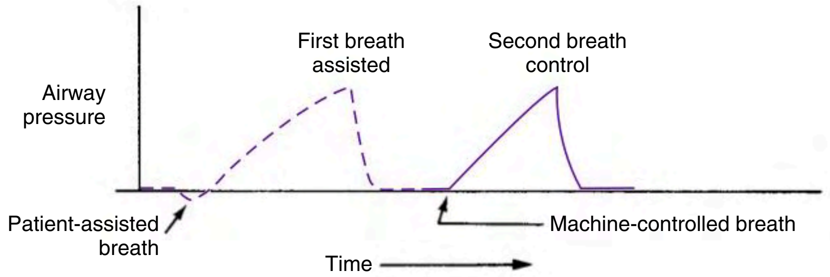


Fig. 3.8 Assist-control pressure curve. A patient-triggered (assisted) breath shows negative deflection of pressure before inspiration, whereas a controlled (time-triggered) breath does not.

BOX 3.6 Ventilator Determination of Actual Breath Delivery During Assisted Ventilation

If a patient occasionally starts a breath independently, the ventilator must determine how long to wait before another breath is needed. As an example, the rate is set at 6 breaths/min. The ventilator determines that it has 10 seconds (60 s/6 breaths) for each breath. If the patient triggers a breath, the ventilator "resets" itself so that it still allows a full 10 seconds after the start of the patient's last breath before it time-triggers another breath.

The maximum pressure that can be attained during inspiration is 25 cm H_2O, but inspiration will end only after 2 seconds have passed. Such a breath is described as a *pressure-limited,* time-cycled breath (cycling ends inspiration [see Termination of the Inspiratory Phase: The Cycling Mechanism section later]).

Pressure Limiting

As the example mentioned earlier illustrates, **pressure limiting** allows pressure to rise to a certain value but not exceed it. Fig. 3.9 shows an example of the internal pneumatic circuit of a piston ventilator. The ventilator pushes a volume of gas into the ventilator circuit, which causes the pressure in the circuit to rise. To prevent excessive pressure from entering the patient's lungs, the clinician sets a high-pressure limit control. When the ventilator reaches the high-pressure limit, excess pressure is vented through a spring-loaded pressure release, or pop-off, valve (see Fig. 3.9). The excess gas pressure is released into the room, just as steam is released by a pressure cooker. In this example, reaching the high-pressure limit does not cycle the ventilator and end inspiration.

The pressure-time and volume-time waveforms shown in Fig. 3.10 illustrate how the set pressure and volume curves would appear for a patient with normal lung function and when the patient's lungs are less compliant. Notice that a higher pressure is required to inflate the stiff lungs, and the pressure limit would be reached before the end of the breath occurs. Consequently, the volume delivered would be less than desired. In other words, volume delivery is reduced because the pressure limit is reached at Time A even though inspiration does not end until Time B (i.e., the breath is time cycled).

Infant ventilators often pressure limit the inspiratory phase but time cycle inspiration. Other examples of pressure-limiting modes are **pressure support** and pressure-controlled ventilation. Remember that when the clinician establishes a set value in pressure-targeted ventilation, the pressure the ventilator delivers to the patient is limited; however, reaching the pressure limit does not end the breath.

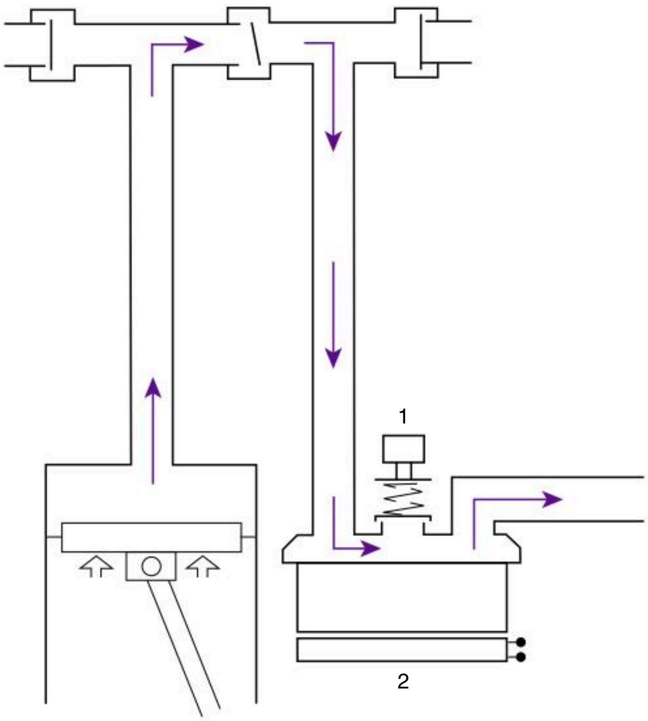


Fig. 3.9 Internal pneumatic circuit on a piston-driven ventilator. *1,* Pressure release valve; *2,* heated humidifier. (Modified from Dupuis Y: *Ventilators: theory and clinical application,* ed 2, St. Louis, MO, 1992, Mosby.)

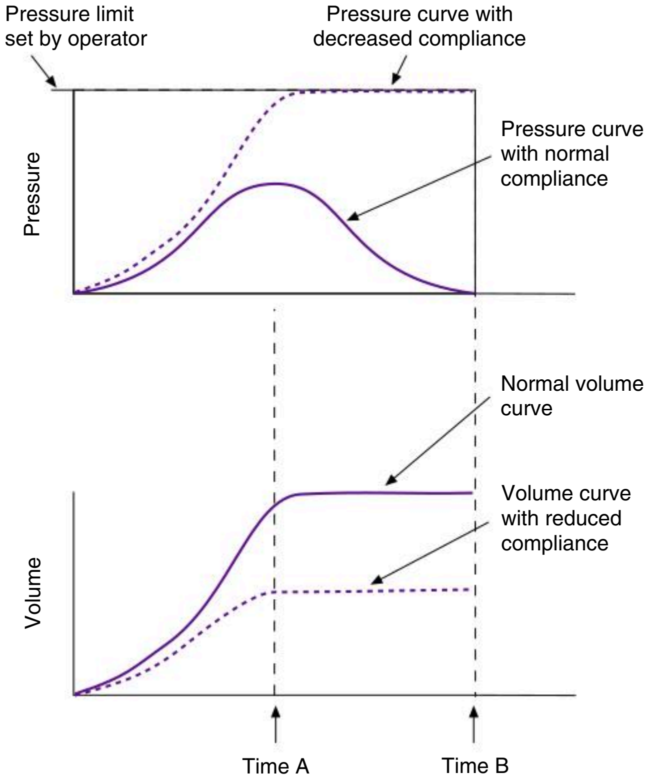


Fig. 3.10 Waveforms from a volume ventilator that delivers a sine wave pressure curve. The pressure and volume waveforms for normal compliance show pressure peaking at Time A and the normal volume delivered by Time A. Inspiration ends at Time B. With reduced compliance, the pressure rises higher during inspiration. Because excess pressure is vented, the pressure reaches a limit and goes no higher. No more flow enters the patient's lungs. Volume delivery has reached its maximum at Time A, when the pressure starts venting. Inspiration is time cycled at Time B. Note that volume delivery is lower when the lungs are stiffer and the pressure is limited. Some of the volume was vented to the air.

Volume Limiting

A volume-limited breath is controlled by an electronically operated valve that measures the flow passing through the ventilator circuit during a specific interval. The clinician can set the volume of gas that the ventilator delivers. With volume limiting, the ventilator may include a bag, bellows, or piston cylinder that contains a fixed volume, which establishes the maximum volume of gas that can be delivered. (NOTE: Reaching that volume does not necessarily end inspiration.) A piston-operated ventilator can be used to provide a simple example of **volume limiting.** Volume is limited to the amount of volume contained in the piston cylinder (see Fig. 3.9). The forward movement of the piston rod or arm controls the duration of inspiration (time-cycled breath).

Ventilators can have more than one limiting feature at a time. In the example just provided, the duration of inspiration could not exceed the excursion time of the piston, and the volume delivered could not exceed the volume in the piston cylinder. Therefore a piston-driven ventilator can be simultaneously volume limited and time limited. (NOTE: Current ventilators that are not piston driven [e.g., Servo-i] provide a volume limit option. When special modes are selected, an actively breathing patient can receive more volume if inspiratory demand increases. The advantage of these ventilators is that the volume delivered to the patient during selected modes is adjusted to meet the patient's increased inspiratory needs.)

Flow Limiting

If gas flow from the ventilator to the patient reaches but does not exceed a maximum value before the end of inspiration, the ventilator is **flow limited;** that is, only a certain amount of flow can be provided. For example, the constant forward motion of a linear-drive piston provides a constant rate of gas delivery to the patient over a certain period. The duration of inspiration is determined by the time it takes the piston rod to move forward.

In other ventilators with volume ventilation, setting the flow control also limits the flow to the patient. Even if the patient makes a strong inspiratory effort, the patient will receive only the maximum flow set by the clinician. For example, if the clinician sets a constant flow of 60 L/min, the maximum flow that the patient can receive is 60 L/min whether or not the patient tries to breathe in at a higher flow. Most current ventilators allow patients to receive increased flow if they have an increased demand because limiting flow is not in the best interest of an actively breathing patient.

Maximum Safety Pressure: Pressure Limiting Versus Pressure Cycling

All ventilators have a feature that allows inspiratory pressure to reach but not exceed a maximum pressure. This maximum safety pressure is used to prevent excessive pressure from damaging a patient's lungs. It is typically set by the operator to a value of 10 cm H_2O above the average peak inspiratory pressure. Manufacturers use various names to describe the maximum pressure control function, such as the *peak/maximum pressure, normal pressure limit, pressure limit, high-pressure limit,* or *upper pressure limit.*

Most adult ventilators pressure cycle (end inspiration) when the set maximum safety pressure limit is reached, as might occur if the patient coughs or if there is an obstruction in the ventilator tubing. Some ventilators allow inspiration to continue while excess pressure is vented to the atmosphere through a pressure safety valve. (In newer intensive care unit [ICU] ventilators, a "floating" exhalation valve prevents pressures from abruptly rising as might occur when the patient coughs [Case Study 3.2]).

It is worth mentioning that ventilator manufacturers set an internal maximum safety pressure. By design, the machine cannot exceed that limit, regardless of the value set by the operator. Ventilator manufacturers usually set internal maximum safety pressure at 120 cm H_2O.

Termination of the Inspiratory Phase: The Cycling Mechanism (Cycle Variable)

The variable that a ventilator uses to end inspiration is called the *cycling mechanism.* The ventilator measures the cycle variable during inspiration and uses this information to govern when the ventilator will end gas flow. Only one of four variables can be used at a given time by the ventilator to end inspiration (i.e., volume, time, flow, or pressure).

Volume-Cycled Ventilation

The inspiratory phase of a **volume-cycled** breath is terminated when the set volume has been delivered. In most cases, the volume remains constant even if the patient's lung characteristics change. The pressures required to deliver the set volume and gas flow, however, will vary as the patient's respiratory system compliance and airway resistance change.

In cases in which the clinician sets an **inspiratory pause,** inspiration will continue until the pause has ended and expiration begins. (The inspiratory pause feature delays opening of the expiratory valve.) In this situation, the breath is volume limited and time cycled. Note that setting an inspiratory pause extends inspiratory time, not inspiratory flow.)

Because most current-generation ICU ventilators do not use volume displacement mechanisms, none of these devices is *technically* classified as volume cycled. (NOTE: The Medtronics Puritan Bennett 740 and 760 are exceptions; these ventilators use linear-drive pistons and can function as true volume-cycled ventilators.[7]) Ventilators such as the Medtronics Puritan Bennett 840/980, Servo-i, CareFusion AVEA, Hamilton Galileo, and Dräger Evita use sensors that determine the gas flow delivered by the ventilator over a specified period, which is then converted to a volume reading (Volume = Flow/Time). These ventilators are considered volume cycled when the targeted volume is delivered and ends the breath.

> **Case Study 3.2**
>
> **Premature Breath Cycling**
>
> A patient receiving volume-controlled ventilation suddenly coughs during the inspiratory phase of the ventilator. A high-pressure alarm sounds, and inspiration ends. Although the set tidal volume is 0.8 L, the measured delivered volume for that breath is 0.5 L. What variable ended inspiration in this example?

Set Volume Versus Actual Delivered Volume

Tubing Compressibility. The volume of gas that leaves the ventilator's outlet is not the volume that enters the patient's lungs. During inspiration, positive pressure builds up in the patient circuit, resulting in expansion of the patient circuit and compression of some of the gas in the circuit (an application of Boyle's law). The compressed gas never reaches the patient's lungs.

In most adult ventilator circuits, about 1 to 3 mL of gas is lost to tubing compressibility for every 1 cm H_2O that is measured by the airway pressure sensor. As a result, a relatively large volume of gas may be compressed in the circuit and never reaches the patient's lungs when high pressures are required to provide ventilation to a patient. Conversely, a patient whose lung compliance is improving can be administered ventilation at lower pressures; therefore less volume is lost to circuit compressibility.

The actual volume delivered to the patient can be determined by measuring the exhaled volume at the endotracheal tube or tracheostomy tube. If the volume is measured at the exhalation valve, it must be corrected for tubing compliance (i.e., the compressible volume). To determine the delivered volume, the volume compressed in the ventilator circuit must be subtracted from the volume measured at the exhalation valve. Most microprocessor-controlled ICU ventilators (e.g., Medtronics Puritan Bennett 840/980, Servo-i) measure and calculate the lost volume and automatically compensate for volume lost to tubing compressibility by increasing the actual volume delivered. For example, the Medtronics PB 840/980 calculates the circuit compliance/compressibility factor during the establishment of ventilation for a new patient setup. The ventilator measures the peak pressure of a breath delivered to the patient and calculates the estimated volume loss caused by circuit compressibility. Then, for the next breath, it adds the volume calculated to the delivered set volume to correct for this loss. (Determination of the compressible volume is discussed in more detail in Chapter 6.)

System Leaks. The volume of gas delivered to the patient may be less than the set volume if a leak in the system occurs. The ventilator may be unable to recognize or compensate for leaks, but the size of the leak can be determined by using an exhaled volume monitor. In cases in which a leak exists, the peak inspiratory pressure will be lower than previous peak inspiratory pressures and a low-pressure alarm may be activated. The volume-time graph can also provide information about leaks (see Chapter 9).

Time-Cycled Ventilation

A breath is considered **time cycled** if the inspiratory phase ends when a predetermined time has elapsed. The interval is controlled by a timing mechanism in the ventilator, which is not affected by the patient's respiratory system compliance or airway resistance. At the specified time, the exhalation valve opens (unless an inspiratory pause has been used) and exhaled air is vented through the exhalation valve. If a constant gas flow is used and the interval is fixed, a tidal volume can be predicted:

$$\text{Tidal volume} = \text{Flow} = \left(\frac{\text{Volume}}{\text{Time}}\right) \times \text{Inspiratory time}$$

The Servo-i and Dräger Evita XL are examples of time-cycled ventilators. These microprocessor-controlled machines can compare the set volume with the set time and calculate the flow required to deliver that volume in that length of time. Consider the following example. A patient's tidal volume (V_T) is set at 1000 mL and the inspiratory time (T_I) is set at 2 seconds. To accomplish this volume delivery in the time allotted, the ventilator would have to deliver a constant flow waveform at a rate of 30 L/min (30 L/60 s = 0.5 L/s) so that 0.5 L/s × 2 s would provide 1.0 L over the desired 2-second inspiratory time.

With time-cycled, volume-controlled ventilation, an increase in airway resistance or a decrease in compliance does *not* affect the flow pattern or volume delivery as long as the working pressures of the ventilator are adequate. Therefore volume delivery in a fixed period remains the same, although the pressures vary. Appropriate alarms should be set to alert the clinician of any significant changes in airway pressures.

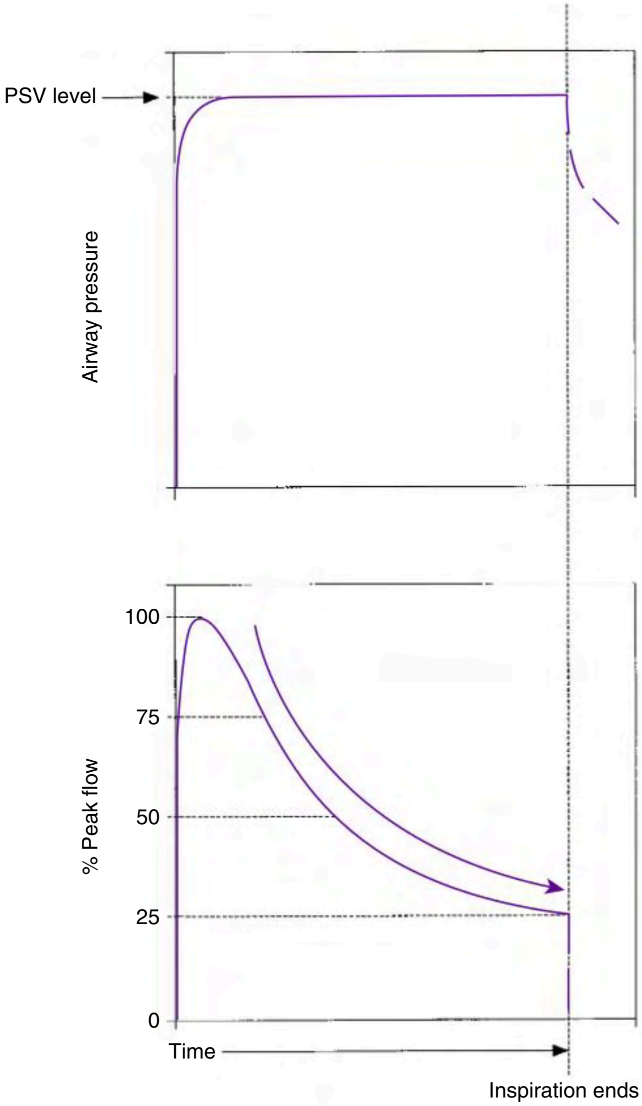


Fig. 3.11 Waveforms from a pressure support breath showing the pressure and flow curves during inspiration. When flow drops to 25% of the peak flow value measured during inspiration, the ventilator flow cycles out of inspiration. *PSV,* Pressure support ventilation. (Modified from Dupuis Y: *Ventilators: theory and clinical application,* ed 2, St. Louis, MO, 1992, Mosby.)

CRITICAL CARE CONCEPT 3.1

Early-generation Bennett ventilators (Bennett PR-1 and PR-2) relied on a Bennett valve to control gas flow to the patient. The principle of operation of these devices is the valve switches from the inspiratory phase to the expiratory phase when flow to the patient drops to 1 to 3 L/min. This lower flow results when the pressure gradient between the alveoli and the ventilator is small and the pressures are nearly equal. Because equal pressure is nearly achieved, along with the low gas flow, these machines are sometimes called *pressure-cycled ventilators.* However, because the predetermined pressure is never actually reached, these ventilators were in reality examples of *flow-cycled* ventilators. (NOTE: The rate control on these machines allowed these devices to function as time-cycled ventilators as long as flow and/or pressure limits were not reached first.)

With time-cycled, pressure-controlled ventilation, both volume and flow vary. Volume (and flow) delivery depends on lung compliance and airway resistance, patient effort (if present), inspiratory time, and set pressure. Time-cycled, pressure-controlled ventilation is commonly called *pressure-controlled ventilation.* Pressure-controlled ventilation is sometimes used because the inspiratory pressure can be limited, which protects the lungs from injury caused by high pressures. However, the variability of tidal volume delivery can be a concern. Alarm settings must be chosen carefully so that the clinician is alerted to any significant changes in the rate and volume.

Flow-Cycled Ventilation

With flow-cycled ventilation, the ventilator cycles into the expiratory phase once the flow has decreased to a predetermined value during inspiration. Volume, pressure, and time vary according to changes in lung characteristics. **Flow cycling** is the most common cycling mechanism in the pressure support mode (Fig. 3.11). In the Medtronics Puritan Bennett 840 ventilator, flow termination occurs when the flow reaches a percentage of the peak inspiratory flow, which is selected by the clinician. In some ventilators, the flow cycle percentage can be adjusted from about 5% to 80%.

Pressure-Cycled Ventilation

During pressure-cycled ventilation, inspiration ends when a set pressure threshold is reached at the mouth or upper airway. The exhalation valve opens, and expiration begins. The volume delivered to the patient depends on the flow delivered, duration of inspiration, patient's lung characteristics, and set pressure.

A disadvantage of pressure-cycled ventilators (e.g., Bird Mark 7) is that these devices deliver variable and generally lower tidal volumes when reductions in compliance and increases in resistance occur. An advantage of pressure-cycled ventilators is that they limit peak airway pressures, which may reduce the damage that can occur when pressures are excessive. These ventilators are most often used to deliver intermittent positive pressure breathing treatments. These devices have also been used for short-term ventilation of patients with relatively stable lung function, such as postoperative patients. It is important that appropriate alarms are operational to ensure the patient is receiving adequate ventilation. Ensuring that the humidification system is adequate is also important. (NOTE: As mentioned previously, **pressure cycling** occurs in volume-controlled breaths when the pressure exceeds the maximum safety high-pressure limit. A high-pressure alarm sounds, and the set tidal volume is not delivered [see Case Study 3.2]).

Inflation Hold (Inspiratory Pause)

Inflation hold is designed to maintain air in the lungs at the end of inspiration, before the exhalation valve opens. During an inflation hold, the inspired volume remains in the patient's lung and the expiratory valve remains closed for a brief period or *pause time.* The pressure reading on the manometer peaks at the end of insufflation and then levels to a plateau (**plateau pressure).** The inflation hold maneuver is sometimes referred to as *inspiratory pause, end-inspiratory pause,* or *inspiratory hold* (Fig. 3.12). As discussed in Chapter 8, the plateau pressure is used to calculate static compliance (Key Point 3.3). The inspiratory pause is used occasionally to increase peripheral distribution of gas and improve oxygenation. Because of the way the pause functions, the normal cycling mechanism no longer ends the breath, resulting in an increase in the inspiratory time and a reduction in the expiratory time.

Expiratory Phase: The Baseline Variable

Definition of Expiration

The *expiratory phase* encompasses the period from the end of inspiration to the beginning of the next breath. During mechanical ventilation, expiration begins when inspiration ends, the expiratory valve opens, and expiratory flow begins. As previously mentioned, opening of the expiratory valve may be delayed if an inflation hold is used to prolong inspiration.

The expiratory phase has received increased attention during the past decade. Clinicians now recognize that air trapping can occur if the expiratory time is too short. Remember that a quiet exhalation is normally a passive event that depends on the elastic recoil of the lungs and thorax and the resistance to airflow offered by the conducting airways. Changes in a patient's respiratory system compliance and airway resistance can alter time constants, which in turn can affect the inspiratory and expiratory times required to achieve effective ventilation. If an adequate amount of time is not provided for exhalation, air trapping and hyperinflation can occur, leading to a phenomenon called auto-PEEP or intrinsic PEEP (see the section on Expiratory Hold later in this chapter).

Key Point 3.3 Calculation of static compliance requires accurate measurement of the plateau pressure. The P_{plat} value is inaccurate if the patient is actively breathing when the measurement is taken.

Baseline Pressure

The baseline variable is the parameter that is generally controlled during exhalation. Although either volume or flow could serve as a baseline variable, pressure is the most practical choice and is used by all modern ventilators.[7]

The pressure level from which a ventilator breath begins is called the *baseline pressure* (see Figs. 3.5 and 3.6). Baseline pressure can be zero (atmospheric), which is also called *zero end-expiratory pressure,* or it can be positive if the baseline pressure is above zero (**positive end-expiratory pressure** [PEEP]).

During the early development of mechanical ventilation, many clinicians thought assisting the expiratory phase was just as important as assisting the inspiratory phase. This was accomplished in one of two ways. With the first method, which was called **negative end-expiratory pressure** (NEEP), negative pressure was applied with a bellows or an entrainment (Venturi) device positioned at the mouth or upper airway to draw air out of the lungs (Fig. 3.13). Another method involved applying positive pressure to the abdominal area, below the diaphragm. With this latter technique, it was thought that applying pressure below the diaphragm would force the air out of the lungs by pushing the visceral organs against the diaphragm (i.e., similar to the effects of performing a Heimlich maneuver).

Under normal circumstances, expiration during mechanical ventilation occurs passively and depends on the passive recoil of the lung. High-frequency oscillation is an exception to this principle. High-frequency oscillation ventilation (HFOV) assists both inspiration and expiration. Oscillators push air into the lungs and pull it back out at extremely high frequencies. These devices function similarly to a speaker system on a stereo. If the mean airway pressure during HFOV is set to equal ambient pressure, the airway pressure oscillates above and below the baseline (i.e., atmospheric pressure). During exhalation, HFOV actually creates a negative transrespiratory pressure. HFOV is most often used for ventilation of infant lungs, although it has also been used occasionally to treat adult patients with acute respiratory distress syndrome (see Chapters 22 and 23). Another technique, called *automatic tube compensation,* allows active removal of air (low pressure) during part of exhalation to reduce the expiratory work of breathing associated with an artificial airway (see Chapter 20 for a more detailed discussion of this technique).

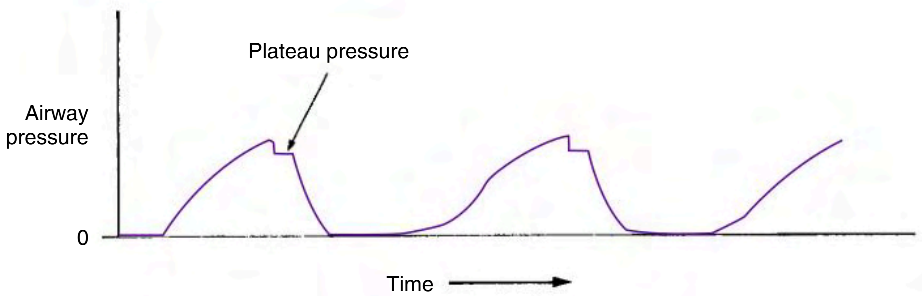


Fig. 3.12 Positive pressure ventilation with an inflation hold, or end-inspiratory pause, leading to a pressure plateau (P_{plat}).