SEVENTH EDITION

Pilbeam's Mechanical Ventilation

Physiological and Clinical Applications

J.M. CAIRO

ELSEVIER

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Dedication

In Memoriam: Cora May Savoy

A generation goes, and a generation comes, but the earth remains forever. The sun rises, and the sun goes down, and hastens to the place where it rises. (Ecclesiastes 1:4–5)

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Preface

As with previous editions of *Pilbeam's Mechanical Ventilation,* the goal of this text is to provide clinicians with a strong physiological foundation for making informed decisions when managing patients receiving mechanical ventilation. The subject matter covered is derived from current evidence-based practices and is written in a manner that allows this text to serve as a resource for both students and practicing clinicians. The seventh edition of *Pilbeam's Mechanical Ventilation* is presented in a concise manner that explains patient-ventilator interactions. Beginning with the most fundamental concepts and expanding to the more advanced topics, the text guides readers through a series of essential concepts and ideas, building upon the information as the reader progresses through the text.

It is apparent to critical care clinicians that implementing effective interprofessional care plans is required to achieve successful outcomes. Respiratory therapists are an integral part of effective interprofessional critical care teams. Their expertise in the areas of mechanical ventilation and respiratory care modalities is particularly valuable considering the pace at which technological advances are occurring in critical care medicine.

The application of mechanical ventilation principles to patient care is one of the most sophisticated respiratory care applications used in critical care medicine, making frequent reviewing helpful, if not necessary. *Pilbeam's Mechanical Ventilation* can be useful to all critical care practitioners, including practicing respiratory therapists, critical care residents and physicians, physician assistants, and critical care nurse practitioners.

Organization

This edition, like previous editions, is organized into a logical sequence of chapters and sections that build upon each other as a reader moves through the book. The initial sections focus on core knowledge and skills needed to apply and initiate mechanical ventilation, whereas the middle and final sections cover specifics of mechanical ventilation patient care techniques, including bedside pulmonary diagnostic testing, hemodynamic testing, pharmacology of patients receiving ventilation, and a concise discussion of ventilator-associated pneumonia, as well as neonatal and pediatric mechanical ventilatory techniques and long-term applications of mechanical ventilation. The inclusion of some helpful appendixes further assists the reader in the comprehension of complex material and an easy-access Glossary defines key terms covered in the chapters.

Features

The valuable learning aids that accompany this text are designed to make it an engaging tool for both educators and students. With clearly defined resources in the beginning of each chapter, students can prepare for the material covered in each chapter through the use of Chapter Outlines, Key Terms, and Learning Objectives.

Along with the abundant use of images and information tables, each chapter contains:

- **Case Studies**: Concise patient vignettes that list pertinent assessment data and pose a critical thinking question to readers to test their understanding of content learned. Answers can be found in Appendix A**.**
- **Critical Care Concepts**: Short questions to engage the readers in applying their knowledge of difficult concepts.
- **Clinical Scenarios**: More comprehensive patient scenarios covering patient presentation, assessment data, and treatment therapies. These scenarios are intended for classroom or group discussion.
- **Key Points:** Highlight important information as key concepts are discussed.

Each chapter concludes with:

- A bulleted Chapter Summary for ease of reviewing chapter content
- Chapter Review Questions (with answers in Appendix A**)**
- A comprehensive list of References at the end of each chapter for those students who wish to learn more about specific topics covered in the text

Finally, several appendixes are included to provide additional resources for readers. These include a Review of Abnormal Physiological Processes, which covers mismatching of pulmonary

perfusion and ventilation, mechanical dead space, and hypoxia. A special appendix on Graphic Exercises gives students extra practice in understanding the interrelationship of flow, volume, and pressure in mechanically ventilated patients. Answer Keys to Case Studies and Critical Care Concepts featured throughout the text and the end-of-chapter Review Questions can help the student track progress in comprehension of the content.

This edition of *Pilbeam's Mechanical Ventilation* has been updated to reflect commonly used equipment and techniques to ensure it is in step with the current modes of therapy. Case Studies, Clinical Scenarios, and Critical Care Concepts are presented throughout the text to emphasize this new information.

Learning Aids

Workbook

The Workbook for *Pilbeam's Mechanical Ventilation* is an easy-to-use guide designed to help the student focus on the most important information presented in the text. The workbook features clinical exercises directly tied to the learning objectives that appear in the beginning of each chapter. Providing the reinforcement and practice that students need, the workbook features exercises such as key term crossword puzzles, critical thinking questions, case studies, waveform analysis, and National Board for Respiratory Care (NBRC)-style multiple-choice questions.

For Educators

Educators using the Evolve website for *Pilbeam's Mechanical Ventilation* have access to an array of resources designed to work in coordination with the text and aid in teaching this topic. Educators may use the Evolve resources to plan class time and lessons, supplement class lectures, or create and develop student exams. These Evolve resources offer:

- More than 800 NBRC-style multiple-choice test questions in ExamView
- PowerPoint Presentation with more than 650 slides featuring key information and helpful images
- An Image Collection of the figures appearing in the book

Jim Cairo, *New Orleans, Louisiana*

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A number of individuals should be recognized for their contributions to this project. I wish to offer my sincere gratitude to Sue Pilbeam for her continued support. I also wish to thank Terry Forrette, MHS, RRT, FAARC, for authoring the chapter on Ventilator Graphics; Rob DiBlasi, RRT-NPS, FAARC, for authoring the chapter on Neonatal and Pediatric Ventilation; and Theresa Gramlich, MS, RRT, and Paul Barraza, RCP, RRT, for their contributions in earlier editions of this text. I also wish to thank Sandra Hinski, MS, RRT-NPS, for authoring the ancillaries that accompany this text and Amanda Dexter, MS, RRT, and Gary Milne, BS, RRT, for their suggestions related to ventilator graphics. As in previous editions, I want to express my sincere appreciation to all of the Respiratory Therapy educators who provided valuable suggestions and comments during the course of writing and editing the seventh edition of *Pilbeam's Mechanical Ventilation*.

I would like to offer special thanks for the guidance provided by the staff of Elsevier throughout this project, particularly Senior Content Strategist, Yvonne Alexopoulos; Senior Content Development Manager, Ellen Wurm-Cutter; Content Development Specialist, Melissa Rawe; Project Manager, Janish Paul; and Publishing Services Manager, Deepthi Unni. Their dedication to this project has been immensely helpful and I feel fortunate to have had the opportunity to work with such a professional group.

I particularly wish to thank my wife, Rhonda for always providing love and support for me and all of our family. Her gift of unconditional love and encouragement inspires me every day.

CHAPTER 1

Basic Terms and Concepts of Mechanical Ventilation

LEARNING OBJECTIVES

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

1. Define *ventilation, external respiration,* and *internal respiration.*
2. Draw a graph showing how intrapleural and alveolar (intrapulmonary) pressures change during spontaneous ventilation and during a positive pressure breath.
3. Define the terms *transpulmonary pressure, transrespiratory pressure, transairway pressure, transthoracic pressure, elastance, compliance,* and *resistance.*
4. Provide the value for intraalveolar pressure throughout inspiration and expiration during normal, quiet breathing.
5. Write the formulas for calculating compliance and resistance.
6. Explain how changes in lung compliance affect the peak pressure measured during inspiration with a mechanical ventilator.
7. Describe the changes in airway conditions that can lead to increased resistance.
8. Calculate the airway resistance given the peak inspiratory pressure, a plateau pressure, and the flow rate.

9. Using a figure showing abnormal compliance or airway resistance, determine which lung unit will fill more quickly or with a greater volume.
10. Compare several time constants, and explain how different time constants will affect volume distribution during inspiration.
11. Give the percentage of passive filling (or emptying) for one, two, three, and five time constants.
12. Briefly discuss the principle of operation of negative pressure, positive pressure, and high-frequency mechanical ventilators.
13. Define peak inspiratory pressure, baseline pressure, positive end-expiratory pressure, and plateau pressure.
14. Describe the measurement of plateau pressure.

KEY TERMS

- Acinus
- Airway opening pressure
- Airway pressure
- Alveolar distending pressure
- Alveolar pressure
- Ascites
- Auto-PEEP
- Bronchopleural fistulas
- Compliance
- Critical opening pressure

- Elastance
- Esophageal pressure
- External respiration
- Extrinsic PEEP
- Fast lung unit
- Functional residual capacity
- Heterogeneous
- High-frequency jet ventilation
- High-frequency oscillatory ventilation
- High-frequency positive pressure ventilation
- Homogeneous
- Internal respiration
- Intrapulmonary pressure
- Intrinsic PEEP
- Manometer
- Mask pressure
- Mouth pressure
- Peak airway pressure
- Peak inspiratory pressure
- Peak pressure
- Plateau pressure

- Positive end-expiratory pressure (PEEP)
- Pressure gradient
- Proximal airway pressure
- Resistance
- Respiration
- Slow lung unit
- Static compliance/static effective compliance
- Time constant
- Transairway pressure
- Transpulmonary pressure
- Transrespiratory pressure
- Transthoracic pressure
- Upper airway pressure
- Ventilation

Physiological Terms and Concepts Related to Mechanical Ventilation

The purpose of this chapter is to provide a brief review of the physiology of breathing and a description of the pressure, volume, and flow events that occur during the respiratory cycle. The effects of changes in lung characteristics (e.g., respiratory compliance and airway resistance) on the mechanics of breathing are also discussed.

Normal Mechanics of Spontaneous Ventilation

Ventilation and Respiration

Spontaneous **ventilation** is simply the movement of air into and out of the lungs. A spontaneous breath is accomplished by contraction of the muscles of inspiration, which causes expansion of the thorax. During a quiet inspiration, the diaphragm descends and enlarges the vertical size of the thoracic cavity while the external intercostal muscles raise the ribs slightly, increasing the circumference of the thorax. Contraction of the diaphragm and external intercostal muscles provides the energy to move air into the lungs and therefore perform the "work" required to overcome the impedance offered by the lungs and chest wall. During a maximal spontaneous inspiration, the accessory muscles of breathing are also used to increase the volume of the thorax.

During a normal quiet expiration, the inspiratory muscles simply relax, the diaphragm moves upward, and the ribs return to their resting position. The volume of the thoracic cavity decreases, and air is forced out of the alveoli. To achieve a maximum expiration (below the end-tidal expiratory level), the accessory muscles of expiration must be used to compress the thorax. Box 1.1 lists the various accessory muscles of breathing.

Respiration involves the exchange of oxygen and carbon dioxide between an organism and its environment. Respiration is typically divided into two components: **external respiration** and **internal respiration**. External respiration involves the diffusion of oxygen and carbon dioxide between the alveoli and the pulmonary capillaries. Oxygenated blood leaving the pulmonary capillaries is carried by the pulmonary veins to the left heart and distributed to the cells of the body via the systemic arteries and capillaries. Internal respiration occurs at the cellular level and involves the exchange of oxygen and carbon dioxide between the systemic capillaries and the cells of the

body. At the cellular level, oxygen diffuses into the cells, where it is used in the oxidation of available substrates (e.g., carbohydrates and lipids) to produce energy. Carbon dioxide, which is a major by-product of aerobic metabolism, diffuses out of the cells into the systemic capillaries. Blood from the systemic capillaries is returned by bulk flow via the systemic veins back to the right heart, the pulmonary arteries, and the pulmonary capillaries.

BOX 1.1 Accessory Muscles of Breathing

Inspiration

Scalene (anterior, medial, and posterior)
Sternocleidomastoids
Pectoralis (major and minor)
Trapezius

Expiration

Rectus abdominis
External oblique
Internal oblique
Transverse abdominal
Serratus (anterior, posterior)
Latissimus dorsi

Gas Flow and Pressure Gradients During Ventilation

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.

Consider what happens during a normal quiet breath. Lung volumes change as a result of gas flow into and out of the airways caused by changes in the pressure gradient between the airway opening and the alveoli. During a spontaneous inspiration, contraction of the inspiratory muscles causes enlargement of the thorax resulting in a decrease (more negative) in intrapleural and alveolar pressure. The alveolar pressure therefore becomes less than the pressure at the airway opening (i.e., the mouth and nose), and gas flows into the lungs. Conversely, during a quiet expiration, relaxation of the inspiratory muscles causes in a decrease in thoracic volume (i.e., diaphragm and external intercostal muscles return to their resting position) and an increase in alveolar pressure. Gas flows out of the lungs during expiration because the pressure in the alveoli is higher than the pressure at the airway opening. It is important to recognize that when the pressure at the airway opening and the pressure in the alveoli are the same, as occurs at the end of expiration, bulk gas flow does not occur because the pressures across the conductive airways are equal (i.e., there is no pressure gradient).

Units of Pressure

Ventilating pressures are commonly measured in centimeters of water pressure (cm H_2O). These pressures are referenced to atmospheric pressure, which is given a baseline value of zero. In other words, although atmospheric pressure is 760 mm Hg or 1034 cm H_2O (1 mm Hg = 1.36 cm H_2O) at sea level, atmospheric pressure is designated as 0 cm H_2O. For example, when airway pressure increases by +20 cm H_2O during a positive pressure breath, the pressure actually increases from 1034 to 1054 cm H_2O. Other units of measure that are becoming more widely used for gas pressures, such as arterial oxygen pressure (P_aO_2) and arterial carbon dioxide pressure (P_aCO_2), are the torr (1 Torr = 1 mm Hg) and the kilopascal ([kPa]; 1 kPa = 7.5 mm Hg). The kilopascal is used in the International System of units. (Box 1.2 provides a summary of common units of measurement for pressure.)

Definitions of Pressures and Gradients in the Lungs

Airway opening pressure (P_{awo}) is most often called **mouth pressure** (P_M) or **airway pressure** (P_{aw}) (Fig. 1.1). Other terms that are often used to describe the airway opening pressure include **upper-airway pressure**, **mask pressure**, and **proximal airway pressure**. [1] Unless pressure is applied at the airway opening, P_{awo} is zero or atmospheric pressure.

BOX 1.2 Pressure Equivalents

1 mm Hg = 1.36 cm H_2O
1 kPa = 7.5 mm Hg
1 Torr = 1 mm Hg
1 atm = 760 mm Hg = 1034 cm H_2O

A similar measurement is the pressure at the body surface (P_{bs}). This is equal to zero (atmospheric pressure) unless the person is placed in a pressurized chamber (e.g., hyperbaric chamber) or a negative pressure ventilator (e.g., iron lung).

Intrapleural pressure (P_{pl}) is the pressure in the potential space between the parietal and visceral pleurae. P_{pl} is normally about −5 cm H_2O at the end of expiration during spontaneous breathing. It is about −10 cm H_2O at the end of inspiration. Because P_{pl} is often difficult to measure in a patient, a related measurement is used, the **esophageal pressure** (P_{es}), which is obtained by placing a specially designed balloon in the esophagus; changes in the balloon pressure are used to estimate pressure and pressure changes in the pleural space. (See Chapter 10 for more information about esophageal pressure measurements.)

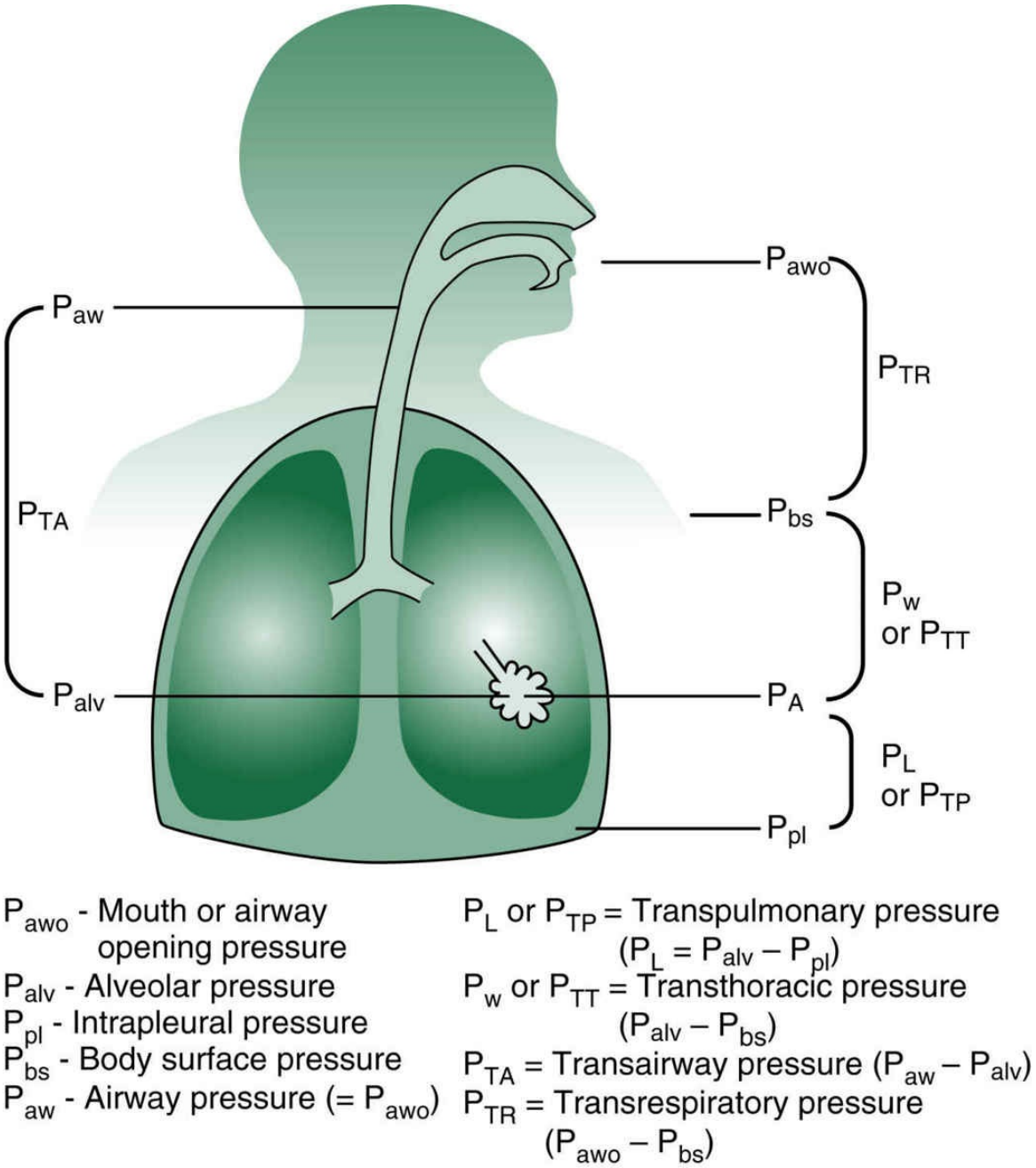

FIG. 1.1 Various pressures and pressure gradients of the respiratory system.
From Kacmarek RM, Stoller JK, Heuer AJ, eds. *Egan's Fundamentals of Respiratory Care.* 11th ed. St. Louis, MO: Elsevier; 2017.

Another commonly measured pressure is alveolar pressure (P_{alv}). This pressure is also called *intrapulmonary pressure* or *lung pressure.* Alveolar pressure normally changes as the intrapleural pressure changes. During spontaneous inspiration, P_{alv} is about −1 cm H_2O,

and during exhalation it is about +1 cm H_2O.

Four basic pressure gradients are used to describe normal ventilation: transairway pressure, transthoracic pressure, transpulmonary pressure (or transalveolar pressure), and transrespiratory pressure (Table 1.1; also see Fig. 1.1).

Transairway Pressure

Transairway pressure (P_{TA}) is the pressure difference between the airway opening and the alveolus: $P_{TA} = P_{awo} - P_{alv}$. It is therefore the pressure gradient required to produce airflow in the conductive airways. It represents the pressure that must be generated to overcome resistance to gas flow in the airways (i.e., airway resistance).

Transthoracic Pressure

Transthoracic pressure (P_W or P_{TT}) is the pressure difference between the alveolar space or lung and the body's surface (P_{bs}): P_W (or P_{TT}) = $P_{alv} - P_{bs}$. It represents the pressure required to expand or contract the lungs and the chest wall at the same time.

Transpulmonary Pressure

Transpulmonary pressure or transalveolar pressure (P_L or P_{TP}) is the pressure difference between the alveolar space and the pleural space (P_{pl}): P_L (or P_{TP}) = $P_{alv} - P_{pl}$. P_L is the pressure required to maintain alveolar inflation and is therefore sometimes called the **alveolar distending pressure**.[2-4] (NOTE: An airway pressure measurement called the **plateau pressure** [P_{plat}] is sometimes substituted for P_{alv}. P_{plat} is measured during a breath-hold maneuver during mechanical ventilation, and the value is read from the ventilator manometer. P_{plat} is discussed in more detail later in this chapter.)

TABLE 1.1

Terms, Abbreviations, and Pressure Gradients for the Respiratory System

Abbreviation	Term	
C	Compliance	
R	Resistance	
R_{aw}	Airway resistance	
P_M	Pressure at the mouth (same as P_{awo})	
P_{aw}	Airway pressure (usually upper airway)	
P_{awo}	Pressure at the airway opening; mouth pressure; mask pressure	
P_{bs}	Pressure at the body surface	
P_{alv}	Alveolar pressure (also P_A)	
P_{pl}	Intrapleural pressure	
C_{st}	Static compliance	
C_{dyn}	Dynamic compliance	
Pressure Gradients		
Transairway pressure (P_{TA})	Airway pressure − alveolar pressure	$P_{TA} = P_{aw} - P_{alv}$
Transthoracic pressure (P_W)	Alveolar pressure − body surface pressure	P_W (or P_{TT}) $= P_{alv} - P_{bs}$
Transpulmonary pressure (P_L)	Alveolar pressure − pleural pressure (also defined as the *transalveolar pressure*)	P_L (or P_{TP}) $= P_{alv} - P_{pl}$
Transrespiratory pressure (P_{TR})	Airway opening pressure − body surface pressure	$P_{TR} = P_{awo} - P_{bs}$

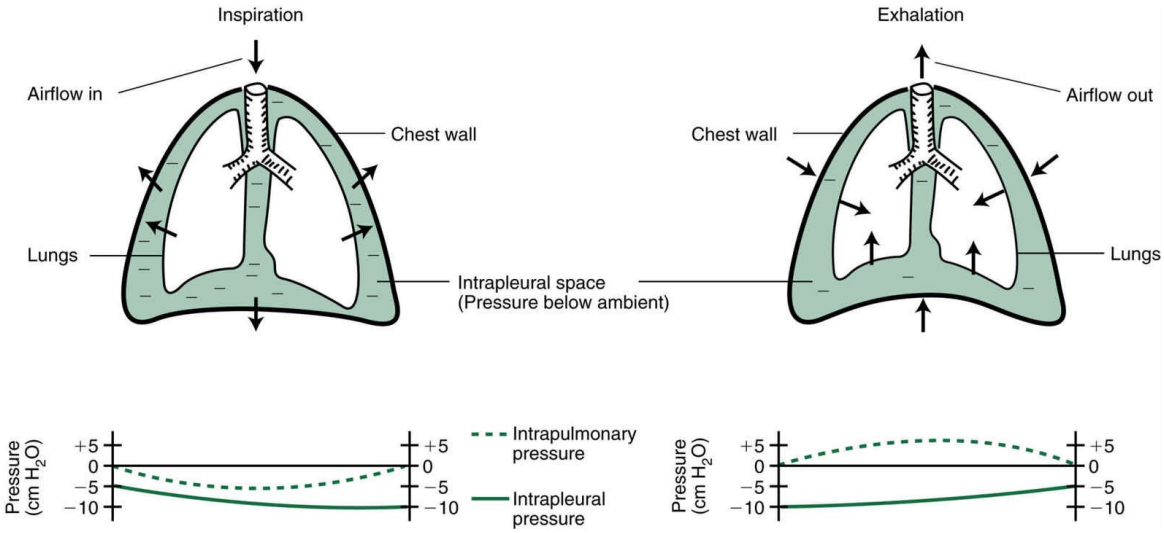

FIG. 1.2 The mechanics of spontaneous ventilation and the resulting pressure waves (approximately normal values). During inspiration, intrapleural pressure (P_{pl}) decreases to −10 cm H_2O. During exhalation, P_{pl} increases from −10 to −5 cm H_2O. (See the text for further description.)

All modes of ventilation increase P_{TP} during inspiration, by either decreasing P_{pl} (negative pressure ventilators) or increasing P_{alv} by increasing pressure at the upper airway (positive pressure

ventilators). During negative pressure ventilation, the pressure at the body surface (P_{bs}) becomes negative and this pressure is transmitted to the pleural space, resulting in a decrease (more negative) in intrapleural pressure (P_{pl}) and an increase in transpulmonary pressure (P_L). During positive pressure ventilation, the P_{bs} remains atmospheric, but the pressures at the airway opening (P_{awo}) and in the conductive airways (airway pressure, or P_{aw}) become positive. Alveolar pressure (P_{alv}) then becomes positive, and transpulmonary pressure (P_L) is increased. *

Transrespiratory Pressure

Transrespiratory pressure (P_{TR}) is the pressure difference between the airway opening and the body surface: $P_{TR} = P_{awo} - P_{bs}$. Transrespiratory pressure is used to describe the pressure required to inflate the lungs during positive pressure ventilation. In this situation, the body surface pressure (P_{bs}) is atmospheric and usually is given the value zero; thus P_{awo} becomes the pressure reading on a ventilator gauge (P_{aw}).

Transrespiratory pressure has two components: transthoracic pressure (the pressure required to overcome elastic recoil of the lungs and chest wall) and transairway pressure (the pressure required to overcome airway resistance). Transrespiratory pressure can therefore be described by the equations $P_{TR} = P_{TT} + P_{TA}$ and $(P_{awo} - P_{bs}) = (P_{alv} - P_{bs}) + (P_{aw} - P_{alv})$.

Consider what happens during a normal, spontaneous inspiration (Fig. 1.2). As the volume of the thoracic space increases, the pressure in the pleural space (intrapleural pressure) becomes more negative in relation to atmospheric pressures. (This is an expected result according to Boyle's law. For a constant temperature, as the volume increases, the pressure decreases.) The intrapleural pressure drops from about −5 cm H_2O at end expiration to about −10 cm H_2O at end inspiration. The negative intrapleural pressure is transmitted to the alveolar space, and the intrapulmonary, or alveolar (P_{alv}), pressure

becomes more negative relative to atmospheric pressure. The transpulmonary pressure (P_L), or the pressure gradient across the lung, widens (Table 1.2). As a result, the alveoli have a negative pressure during spontaneous inspiration.

The pressure at the airway opening or body surface is still atmospheric, creating a pressure gradient between the mouth (zero) and the alveolus of about −3 to −5 cm H_2O. The transairway pressure gradient (P_{TA}) is approximately (0 − [−5]), or 5 cm H_2O. Air flows from the mouth or nose into the lungs and the alveoli expand. When the volume of gas builds up in the alveoli and the pressure returns to zero, airflow stops. This marks the end of inspiration; no more gas moves into the lungs because the pressure at the mouth and in the alveoli equals zero (i.e., atmospheric pressure) (see Fig. 1.2).

During expiration, the muscles relax and the elastic recoil of the lung tissue results in a decrease in lung volume. The thoracic volume decreases to resting, and the intrapleural pressure returns to about −5 cm H_2O. Notice that the pressure inside the alveolus during exhalation increases and becomes slightly positive (+5 cm H_2O). As a result, pressure is now lower at the mouth than inside the alveoli and the transairway pressure gradient causes air to move out of the lungs. When the pressure in the alveoli and that in the mouth are equal, exhalation ends.

TABLE 1.2

Changes in Transpulmonary Pressure [a] Under Varying Conditions

Pressure	End Expiration	End Inspiration
Passive Spontaneous Ventilation		
Intraalveolar (intrapulmonary)	0 cm H_2O	0 cm H_2O
Intrapleural	−5 cm H_2O	−10 cm H_2O
Transpulmonary	$P_L = 0 - (-5) = +5$ cm H_2O	$P_L = 0 - (-10) = 10$ cm H_2O
Negative Pressure Ventilation		
Intraalveolar (intrapulmonary)	0 cm H_2O	0 cm H_2O
Intrapleural	−5 cm H_2O	−10 cm H_2O
Transpulmonary	$P_L = 0 - (-5) = +5$ cm H_2O	$P_L = 0 - (-10) = 10$ cm H_2O
Positive Pressure Ventilation		
Intraalveolar (intrapulmonary)	0 cm H_2O	9-12 cm H_2O[b]
Intrapleural	−5 cm H_2O	2-5 cm H_2O[b]
Transpulmonary	$P_L = 0 - (-5) = +5$ cm H_2O	$P_L = 10 - (2) = +8$ cm H_2O[b]

[a] $P_L = P_{alv} - P_{pl}$.

[b] Applied pressure is +15 cm H_2O.

Lung Characteristics

Normally, two types of forces oppose inflation of the lungs: elastic forces and frictional forces. Elastic forces arise from the elastic properties 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.

Two parameters are often used to describe the mechanical properties of the respiratory system and the elastic and frictional forces opposing lung inflation: *compliance* and *resistance.*

Compliance

The **compliance** (C) of any structure can be described as the relative ease with which the structure distends. It can be defined as the inverse of **elastance** (e), where *elastance* is the tendency of a structure to return to its original form after being stretched or acted on by an outside force. Thus $C = 1/e$ or $e = 1/C$. The following examples illustrate this principle. A balloon that is easy to inflate is said to be very compliant (it demonstrates reduced elasticity), whereas a balloon that is difficult to inflate is considered not very compliant (it has increased elasticity). In a similar way, consider the comparison of a golf ball and a tennis ball. The golf ball is more elastic than the tennis ball because it tends to retain its original form; a considerable amount of force must be applied to the golf ball to compress it. A tennis ball, on the other hand, can be compressed more easily than the golf ball, so it can be described as less elastic and more compliant.

In the clinical setting, compliance measurements are used to describe the elastic forces that oppose lung inflation. More specifically, the compliance of the respiratory system is determined by measuring the change (Δ) of volume (V) that occurs when pressure (P) is applied to the system: $C = \Delta V/\Delta P$. Volume typically is measured in liters or milliliters and pressure in centimeters of water pressure. It is

important to understand that the compliance of the respiratory system is the sum of the compliances of both the lung parenchyma and the surrounding thoracic structures. In a spontaneously breathing individual, the total respiratory system compliance is about 0.1 L/cm H_2O (100 mL/cm H_2O); however, it can vary considerably, depending on a person's posture, position, and whether he or she is actively inhaling or exhaling during the measurement. It can range from 0.05 to 0.17 L/cm H_2O (50 to 170 mL/cm H_2O). For intubated and mechanically ventilated patients with normal lungs and a normal chest wall, compliance varies from 40 to 50 mL/cm H_2O in men and 35 to 45 mL/cm H_2O in women to as high as 100 mL/cm H_2O in either gender (Key Point 1.1).

Key Point 1.1

Normal compliance in spontaneously breathing patients: 0.05 to 0.17 L/cm H_2O or 50 to 170 mL/cm H_2O

Normal compliance in intubated patients: Males: 40 to 50 mL/cm H_2O, up to 100 mL/cm H_2O; Females: 35 to 45 mL/cm H_2O, up to 100 mL/cm H_2O

Changes in the condition of the lungs or chest wall (or both) affect total respiratory system compliance and the pressure required to inflate the lungs. Diseases that reduce the compliance of the lungs or chest wall increase the pressure required to inflate the lungs. Acute respiratory distress syndrome and kyphoscoliosis are examples of pathological conditions associated with reductions in lung compliance and thoracic compliance, respectively. Conversely, emphysema is an example of a pulmonary condition in which pulmonary compliance is increased as a result of a loss of lung elasticity. With emphysema, less pressure is required to inflate the lungs.

Critical Care Concept 1.1 presents an exercise in which students can test their understanding of the compliance equation.

Critical Care Concept 1.1 Calculate Pressure

Calculate the amount of pressure needed to attain a tidal volume of 0.5 L (500 mL) for a patient with a normal respiratory system compliance of 0.1 L/cm H_2O.

For patients receiving mechanical ventilation, compliance measurements are made during static or no-flow conditions (e.g., this is the airway pressure measured at end inspiration; it is designated as the plateau pressure). Thus these compliance measurements are referred to as **static compliance or static effective compliance**. The tidal volume used in this calculation is determined by measuring the patient's exhaled volume near the patient connector (Fig. 1.3). Box 1.3 shows the formula for calculating static compliance (C_S) for a ventilated patient. Note that although this calculation technically includes the recoil of the lungs and thorax, thoracic compliance generally does not change significantly in a ventilated patient. (NOTE: It is important to understand that if a patient actively inhales or exhales during measurement of a plateau pressure, the resulting value will be inaccurate. Active breathing can be a particularly difficult issue when patients are tachypneic, such as when a patient is experiencing respiratory distress.)

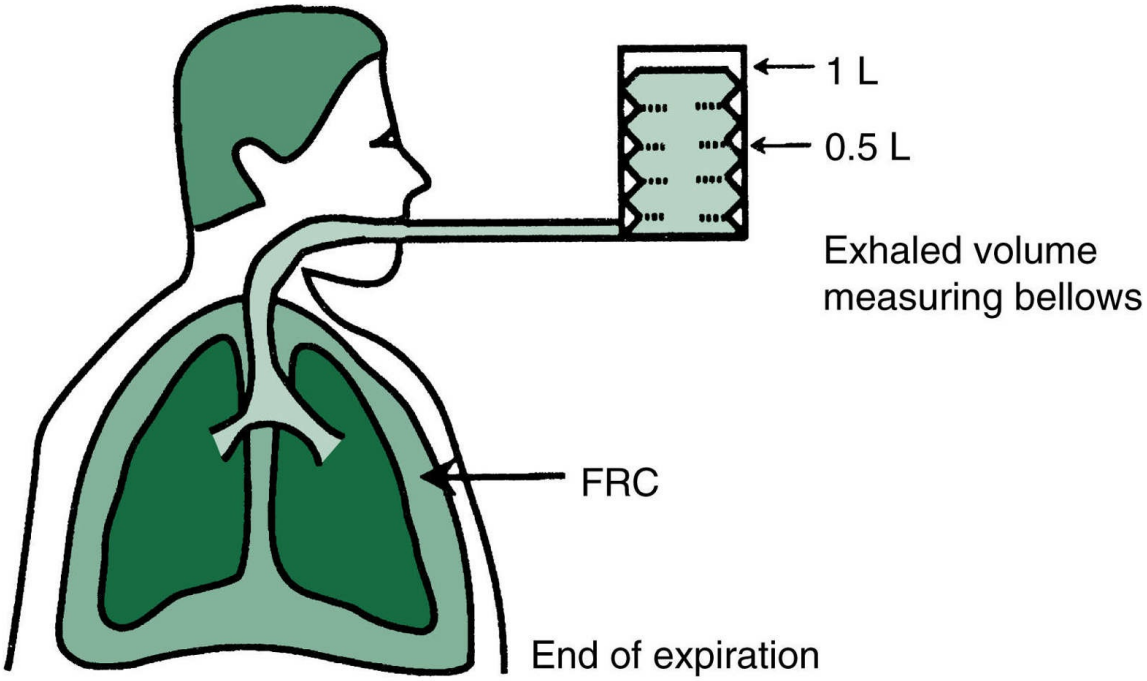

FIG. 1.3 A volume device (bellows) is used to illustrate the measurement of exhaled volume. Ventilators typically use a flow transducer to measure the exhaled tidal volume. The functional residual capacity (FRC) is the amount of air that remains in the lungs after a normal exhalation.

BOX 1.3 Equation for Calculating Static Compliance

$$C_S = (\text{Exhaled tidal volume})/(\text{Plateau pressure} - \text{EEP})$$

$$C_S = V_T/(P_{plat} - \text{EEP})\ ^*$$

---

* EEP is the end-expiratory pressure, which some clinicians call the *baseline pressure;* it is the baseline from which the patient breathes. When positive end-expiratory pressure (PEEP) is administered, it is the EEP value used in this calculation.

Resistance

Resistance is a measurement of the frictional forces that must be overcome during breathing. These frictional forces are the result of the anatomical structure of the airways and the tissue viscous resistance offered by the lungs and adjacent tissues and organs.

As the lungs and thorax move during ventilation, the movement and displacement of structures such as the lungs, abdominal organs, rib cage, and diaphragm create resistance to breathing. Tissue viscous resistance remains constant under most circumstances. For example, an obese patient or one with fibrosis has increased tissue resistance, but the tissue resistance usually does not change significantly when these patients are mechanically ventilated. On the other hand, if a patient develops **ascites**, or fluid accumulation in the peritoneal cavity, tissue resistance increases.

The resistance to airflow through the conductive airways *(airway resistance)* depends on the gas viscosity, the gas density, the length and diameter of the tube, and the flow rate of the gas through the tube, as defined by Poiseuille's law. During mechanical ventilation, viscosity, density, and tube or airway length remain fairly constant. In contrast, the diameter of the airway lumen can change considerably and affect the flow of the gas into and out of the lungs. The diameter of the airway lumen and the flow of gas into the lungs can decrease as a result of bronchospasm, increased secretions, mucosal edema, or kinks in the endotracheal tube. The rate at which gas flows into the lungs also can be controlled on most mechanical ventilators.

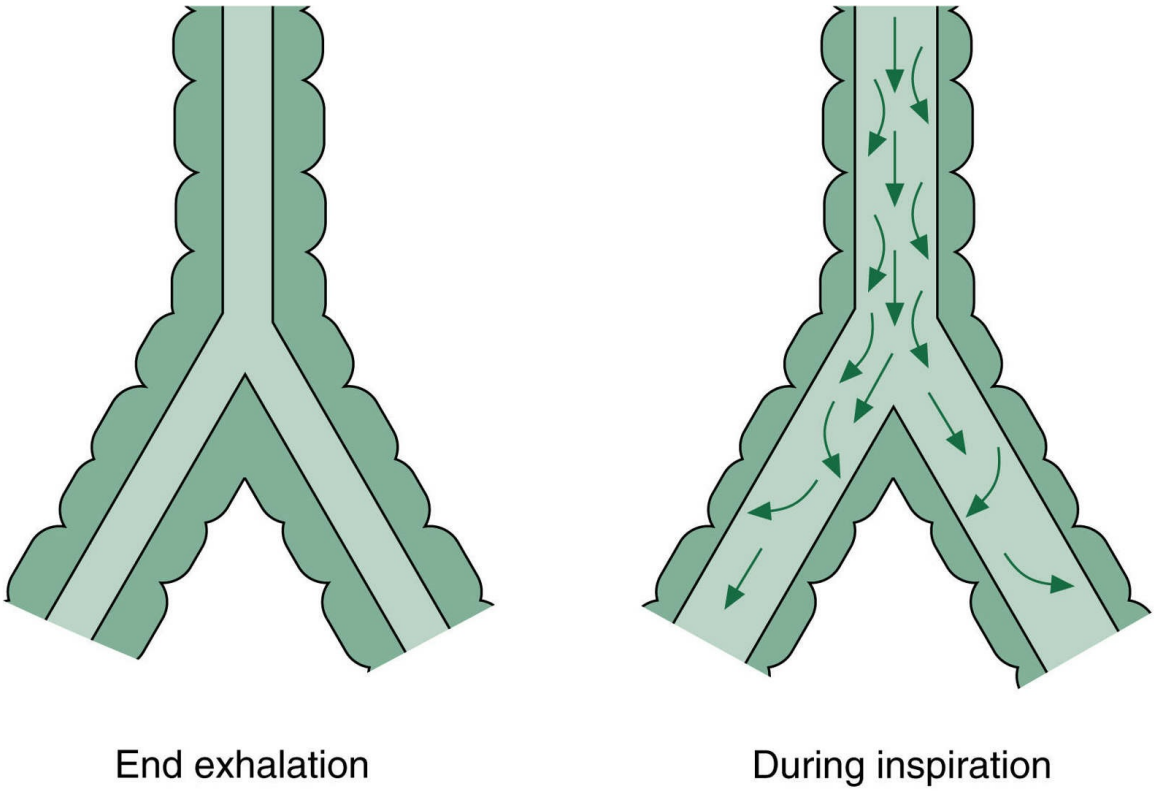

FIG. 1.4 Expansion of the airways during inspiration. (See the text for further explanation.)

At the end of the expiratory cycle, before the ventilator cycles into inspiration, normally no flow of gas occurs; the alveolar and mouth pressures are equal. Because flow is absent, resistance to flow is also absent. When the ventilator cycles on and creates a positive pressure at the mouth, the gas attempts to move into the lower-pressure zones in the alveoli. However, this movement is impeded or even blocked by having to pass through the endotracheal tube and the upper conductive airways. Some molecules are slowed as they collide with the tube and the bronchial walls; in doing this, they exert energy (pressure) against the passages, which causes the airways to expand (Fig. 1.4); as a result, some of the gas molecules (pressure) remain in the airway and do not reach the alveoli. In addition, as the gas molecules flow through the airway and the layers of gas flow over each other, resistance to flow, called *viscous resistance,* occurs.

The relationship of gas flow, pressure, and resistance in the airways is described by the equation for airway resistance, $R_{aw} = P_{TA}/\text{flow}$,

where R_{aw} is airway resistance and P_{TA} is the pressure difference between the mouth and the alveolus, or the transairway pressure (Key Point 1.2). *Flow* is the gas flow measured during inspiration. Resistance is usually expressed in centimeters of water per liter per second (cm H_2O/[L/s]). In normal, conscious individuals with a gas flow of 0.5 L/s, resistance is about 0.6 to 2.4 cm H_2O/(L/s) (Box 1.4). The actual amount varies over the entire respiratory cycle. The variation occurs because flow during spontaneous ventilation usually is slower at the beginning and end of the cycle and faster in the middle portion of the cycle. *

Key Point 1.2

$R_{aw} = (PIP - P_{plat})/flow$ (where PIP is peak inspiratory pressure); or $R_{aw} = P_{TA}/flow$; example:

$$R_{aw} = \left[\frac{40 - 25 \text{ cm } H_2O}{1 \text{ (L/s)}}\right] = 15 \text{ cm } H_2O/\text{(L/s)}$$

BOX 1.4 Normal Resistance Values

Unintubated Patient

0.6 to 2.4 cm H_2O/(L/s) at 0.5 L/s flow

Intubated Patient

Approximately 6 cm H_2O/(L/s) or higher (airway resistance increases as endotracheal tube size decreases)

Airway resistance is increased when an artificial airway is inserted. The smaller internal diameter of the tube creates greater resistance to flow (resistance can be increased to 5 to 7 cm H_2O/[L/s]). As mentioned, pathological conditions also can increase airway resistance by decreasing the diameter of the airways. In conscious, unintubated patients with emphysema and asthma, resistance may range from 13 to 18 cm H_2O/(L/s). Still higher values can occur with other severe types of obstructive disorders.

Several challenges are associated with increased airway resistance. With greater resistance, a greater pressure drop occurs in the conducting airways and less pressure is available to expand the alveoli. As a consequence, a smaller volume of gas is available for gas exchange. The greater resistance also requires that more force be exerted to maintain adequate gas flow. To achieve this force, spontaneously breathing patients use the accessory muscles of inspiration. This generates more negative intrapleural pressures and a greater pressure gradient between the upper airway and the pleural space to achieve gas flow. The same occurs during mechanical ventilation; more pressure must be generated by the ventilator to try to "blow" the air into the patient's lungs through obstructed airways or through a small endotracheal tube.

Measuring Airway Resistance

Airway resistance pressure is not easily measured; however, the transairway pressure can be calculated: $P_{TA} = PIP - P_{plat}$. This allows determination of how much pressure is delivered to the airways and how much to alveoli. For example, if the peak pressure during a mechanical breath is 25 cm H_2O and the plateau pressure (i.e., pressure at end inspiration using a breath hold) is 20 cm H_2O, the pressure lost to the airways because of airway resistance is 25 cm H_2O − 20 cm H_2O = 5 cm H_2O. In fact, 5 cm H_2O is about the normal

amount of pressure (P_{TA}) lost to airway resistance (R_{aw}) with a proper-sized endotracheal tube in place. In another example, if the peak pressure during a mechanical breath is 40 cm H_2O and the plateau pressure is 25 cm H_2O, the pressure lost to airway resistance is 40 cm H_2O − 25 cm H_2O = 15 cm H_2O. This value is high and indicates an increase in R_{aw} (see Box 1.4).

Many mechanical ventilators allow the therapist to choose a specific constant flow setting. Monitors are incorporated into the user interface to display peak airway pressures, plateau pressure, and the actual gas flow during inspiration. With this additional information, airway resistance can be calculated. For example, let us assume that the flow is set at 60 L/min, the peak inspiratory pressure (PIP) is 40 cm H_2O, and the P_{plat} is 25 cm H_2O. The P_{TA} is therefore 15 cm H_2O. To calculate airway resistance, flow is converted from liters per minute to liters per second (60 L/min = 60 L/60 s = 1 L/s). The values then are substituted into the equation for airway resistance, R_{aw} = (PIP − P_{plat})/flow:

$$R_{aw} = \left[\frac{40 - 25 \text{ cm } H_2O}{1 \text{ (L/s)}}\right] = 15 \text{ cm } H_2O/_{(L/s)}$$

For an intubated patient, this is an example of elevated airway resistance. The elevated R_{aw} may be caused by increased secretions, mucosal edema, bronchospasm, or an endotracheal tube that is too small.

Ventilators with microprocessors can provide real-time calculations of airway resistance. It is important to recognize that where pressure and flow are measured can affect the airway resistance values. Measurements taken inside the ventilator may be less accurate than those obtained at the airway opening. For example, if a ventilator measures flow at the exhalation valve and pressure on the inspiratory

side of the ventilator, these values incorporate the resistance to flow through the ventilator circuit and not just patient airway resistance. Clinicians must therefore know how the ventilator obtains measurements to fully understand the resistance calculation that is reported.

Case Study 1.1 provides an exercise to test your understanding of airway resistance and respiratory compliance measurements.

Case Study 1.1 Determine Static Compliance (C_S) and Airway Resistance (R_{aw})

An intubated, 36-year-old woman diagnosed with pneumonia is being ventilated with a volume of 0.5 L (500 mL). The peak inspiratory pressure is 24 cm H_2O, P_{plat} is 19 cm H_2O, and baseline pressure is 0. The inspiratory gas flow is constant at 60 L/min (1 L/s).

What are the static compliance and airway resistance?
Are these normal values?

Time Constants

Regional differences in compliance and resistance exist throughout the lungs. That is, the compliance and resistance values of a terminal respiratory unit **(acinus)** may be considerably different from those of another unit. Thus the characteristics of the lung are **heterogeneous ,** not **homogeneous**. Indeed, some lung units may have normal compliance and resistance characteristics, whereas others may demonstrate pathophysiological changes, such as increased resistance, decreased compliance, or both.

Alterations in C and R_{aw} affect how rapidly lung units fill and empty. Each small unit of the lung can be pictured as a small, inflatable balloon attached to a short drinking straw. The volume the balloon receives in relation to other small units depends on its compliance and resistance, assuming that other factors are equal (e.g., intrapleural pressures and the location of the units relative to different lung zones).

Fig. 1.5 provides a series of graphs illustrating the filling of the lung during a quiet breath. A lung unit with normal compliance and airway resistance will fill within a normal length of time and with a normal volume (see Fig. 1.5, *A*). If the lung unit has normal resistance but is stiff (low compliance), it will fill rapidly (see Fig. 1.5, *B*). For example, when a new toy balloon is first inflated, considerable effort is required to start the inflation (i.e., high pressure is required to overcome the **critical opening pressure** of the balloon to allow it to start filling). When the balloon inflates, it does so very rapidly at first. It also deflates very quickly. Notice, however, that if a given pressure is applied to a stiff lung unit and a normal unit for the same length of time, a much smaller volume will be delivered to the stiff lung unit (compliance equals volume divided by pressure) compared with the volume delivered to the normal unit.

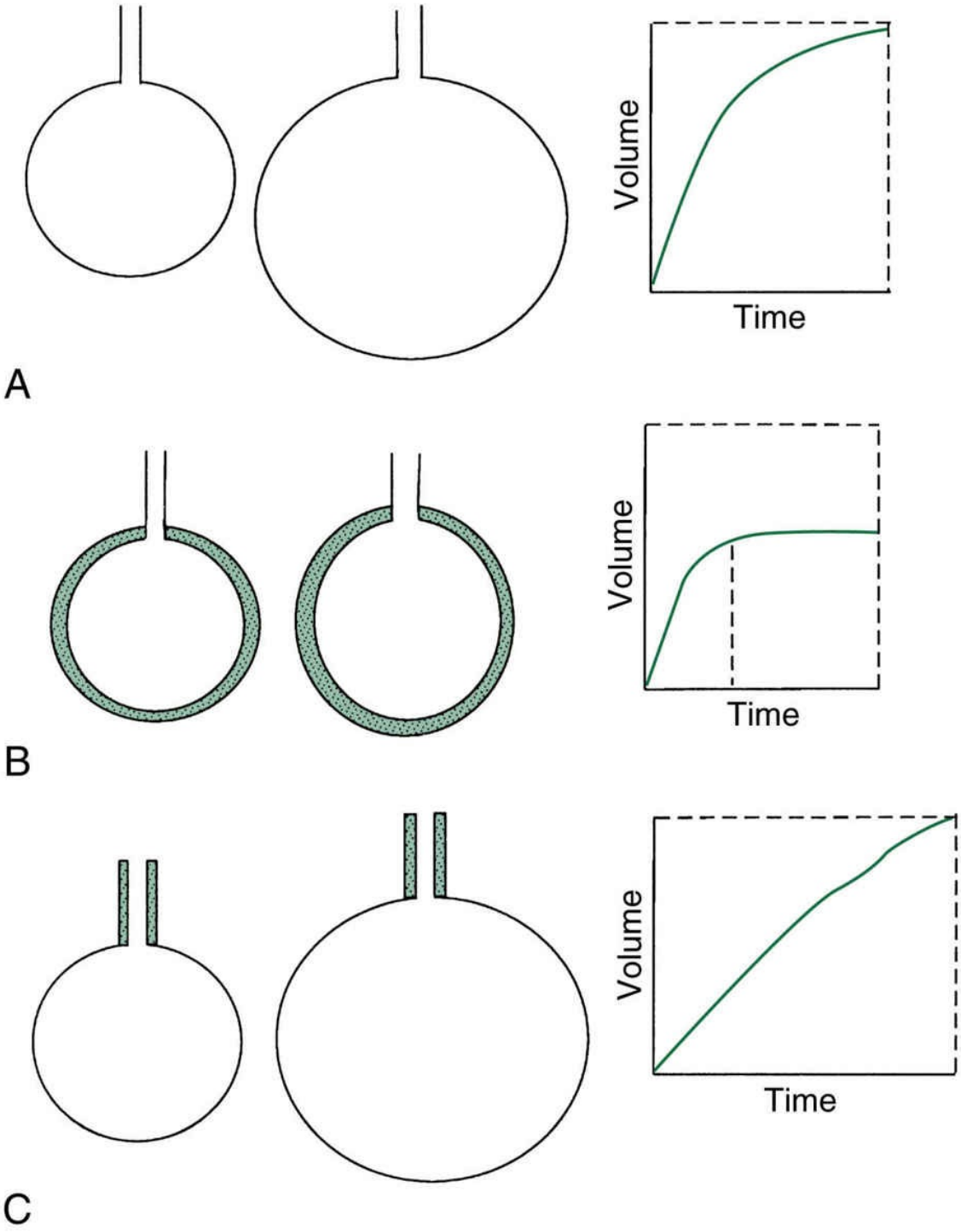

FIG. 1.5 (A) Filling of a normal lung unit. (B) A low-compliance unit, which fills quickly but with less air. (C) Increased resistance; the unit fills slowly. If inspiration were to end at the same time as in (A), the volume in (C) would be lower.

Now consider a balloon (lung unit) that has normal compliance but

the straw (airway) is very narrow (high airway resistance) (see Fig. 1.5C). In this case the balloon (lung unit) fills very slowly. The gas takes much longer to flow through the narrow passage and reach the balloon (acinus). If gas flow is applied for the same length of time as in a normal situation, the resulting volume is smaller.

The length of time lung units required to fill and empty can be determined. The product of compliance (C) and resistance (R_{aw}) is called a **time constant**. For any value of C and R_{aw}, the time constant always equals the length of time (in seconds) required for the lungs to inflate or deflate to a certain amount (percentage) of their volume. Box 1.5 shows the calculation of one time constant for a lung unit with a compliance of 0.1 L/cm H_2O and an airway resistance of 1 cm H_2O/(L/s). One time constant equals the amount of time it takes for 63% of the volume to be inhaled (or exhaled), two time constants represent that amount of time for about 86% of the volume to be inhaled (or exhaled), three time constants equal the time for about 95% to be inhaled (or exhaled), and four time constants is the time required for 98% of the volume to be inhaled (or exhaled) (Fig. 1.6). [4-6] In the example in Box 1.5, with a time constant of 0.1 s, 98% of the volume fills (or empties) the lungs in four time constants, or 0.4 s.

BOX 1.5 Calculation of Time Constant

Time constant = $C \times R_{aw}$
Time constant = 0.1 L/cm $H_2O \times 1$ cm H_2O/(L/s)
Time constant = 0.1 s

In a patient with a time constant of 0.1 s, 63% of inhalation (or exhalation) occurs in 0.1 s; that is, 63% of the volume is inhaled (or exhaled) in 0.1 s, and 37% of the volume remains to be exchanged.

After five time constants, the lung is considered to contain 100% of

tidal volume to be inhaled or 100% of tidal volume has been exhaled. In the example in Box 1.5, five time constants would equal 5 × 0.1 s, or 0.5 s. Thus, in half a second, a normal lung unit, as described here, would be fully expanded or deflated to its end-expiratory volume (Key Point 1.3).

Key Point 1.3

Time constants approximate the amount of time required to fill or empty a lung unit.

Calculation of time constants is important when setting the ventilator's inspiratory time and expiratory time. An inspiratory time less than three time constants may result in incomplete delivery of the tidal volume. Prolonging the inspiratory time allows even distribution of ventilation and adequate delivery of tidal volume. Five time constants should be considered for the inspiratory time, particularly in pressure ventilation, to ensure adequate volume delivery (see Chapter 2 for more information on pressure ventilation). It is important to recognize, however, that if the inspiratory time is too long, the respiratory rate may be too low to achieve effective minute ventilation.

An expiratory time of less than three time constants may lead to incomplete emptying of the lungs. This can increase the functional residual capacity and cause trapping of air in the lungs. Some clinicians think that using the 95% to 98% volume emptying level (three or four time constants) is adequate for exhalation. [5,6] Exact time settings require careful observation of the patient and measurement of end-expiratory pressure to determine which time is better tolerated.

In summary, lung units can be described as fast or slow. **Fast lung units** have short time constants and take less time to fill and empty. Short time constants are associated with normal or low airway resistance and decreased compliance, such as occurs in a patient with interstitial fibrosis. It is important to recognize, however, that these

lung units will typically require increased pressure to achieve a normal volume. In contrast, **slow lung units** have long time constants, which require more time to fill and empty compared with a normal or fast lung unit. Slow lung units have increased resistance or increased compliance, or both, and are typically found in patients with pulmonary emphysema.

It must be kept in mind that the lung is rarely uniform across ventilating units. Some units fill and empty quickly, whereas others do so more slowly. Clinically, compliance and airway resistance measurements reflect a patient's overall lung function, and clinicians must recognize this fact when using these data to guide treatment decisions.

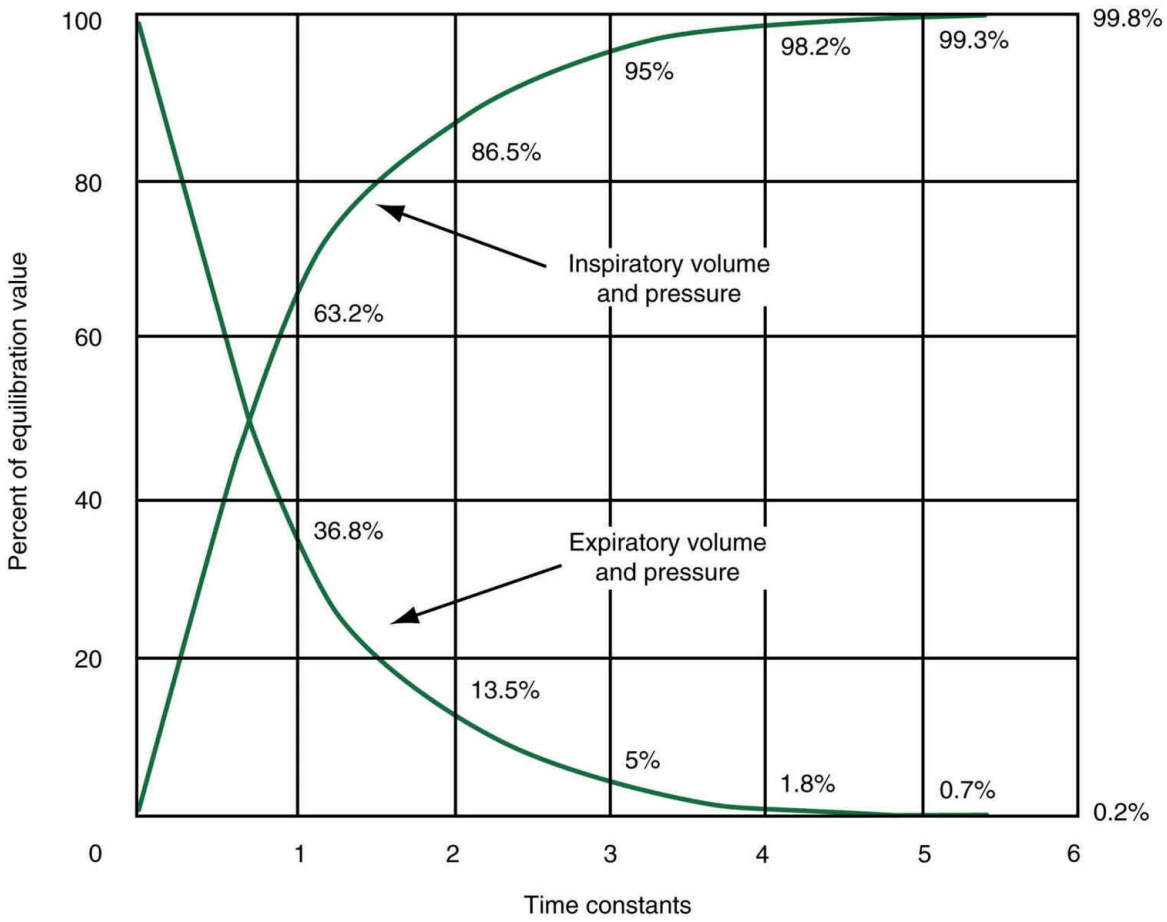

FIG. 1.6 The time constant (compliance × resistance) is a measure of how long the respiratory system takes to passively exhale (deflate) or inhale (inflate).

From Kacmarek RM, Stoller JK, Heuer AJ, eds. *Egan's Fundamentals of Respiratory Care*, 11th ed, St. Louis, MO: Elsevier; 2017.

Types of Ventilators and Terms Used in Mechanical Ventilation

Various types of mechanical ventilators are used clinically. The following section provides a brief description of the terms commonly applied to mechanical ventilation.

Types of Mechanical Ventilation

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.

Negative Pressure Ventilation

Negative pressure ventilation (NPV) attempts to mimic the function of the respiratory muscles to allow breathing through normal physiological mechanisms. A good example of negative pressure ventilators is the tank ventilator, or "iron lung." With this device, the patient's head and neck are exposed to ambient pressure while the thorax and the rest of the body are enclosed in an airtight container that is subjected to negative pressure (i.e., pressure less than atmospheric pressure). Negative pressure generated around the thoracic area is transmitted across the chest wall, into the intrapleural space, and finally into the intraalveolar space.

With negative pressure ventilators, as the intrapleural space becomes negative, the space inside the alveoli becomes increasingly negative in relation to the pressure at the airway opening (atmospheric pressure). This pressure gradient results in the movement of air into the lungs. In this way, negative pressure ventilators resemble normal lung mechanics. Expiration occurs when the negative pressure around the chest wall is removed. The normal elastic recoil of the lungs and chest wall causes air to flow out of the lungs passively (Fig. 1.7).

Negative pressure ventilators do provide several advantages. The upper airway can be maintained without the use of an endotracheal tube or tracheostomy. Patients receiving negative pressure ventilation can talk and eat while being ventilated. Negative pressure ventilation has fewer physiological disadvantages in patients with normal cardiovascular function than does positive pressure ventilation. [7-10] In hypovolemic patients, however, a normal cardiovascular response is

not always present. As a result, patients can have significant pooling of blood in the abdomen and reduced venous return to the heart. [9,10] Additionally, difficulty gaining access to the patient can complicate care activities (e.g., bathing and turning).

The use of negative pressure ventilators declined considerably in the early 1980s, and currently they are rarely used in hospitals. Other methods of creating negative pressure (e.g., chest cuirass, Poncho wrap, and Porta-Lung) have been used in home care to treat patients with chronic respiratory failure associated with neuromuscular diseases (e.g., polio and amyotrophic lateral sclerosis). [8-13] More recently, these devices have been replaced with noninvasive positive pressure ventilators (NIV) that use a mask, a nasal device, or a tracheostomy tube as a patient interface. Chapters 19 and 21 provide additional information on the use of NIV and NPV.

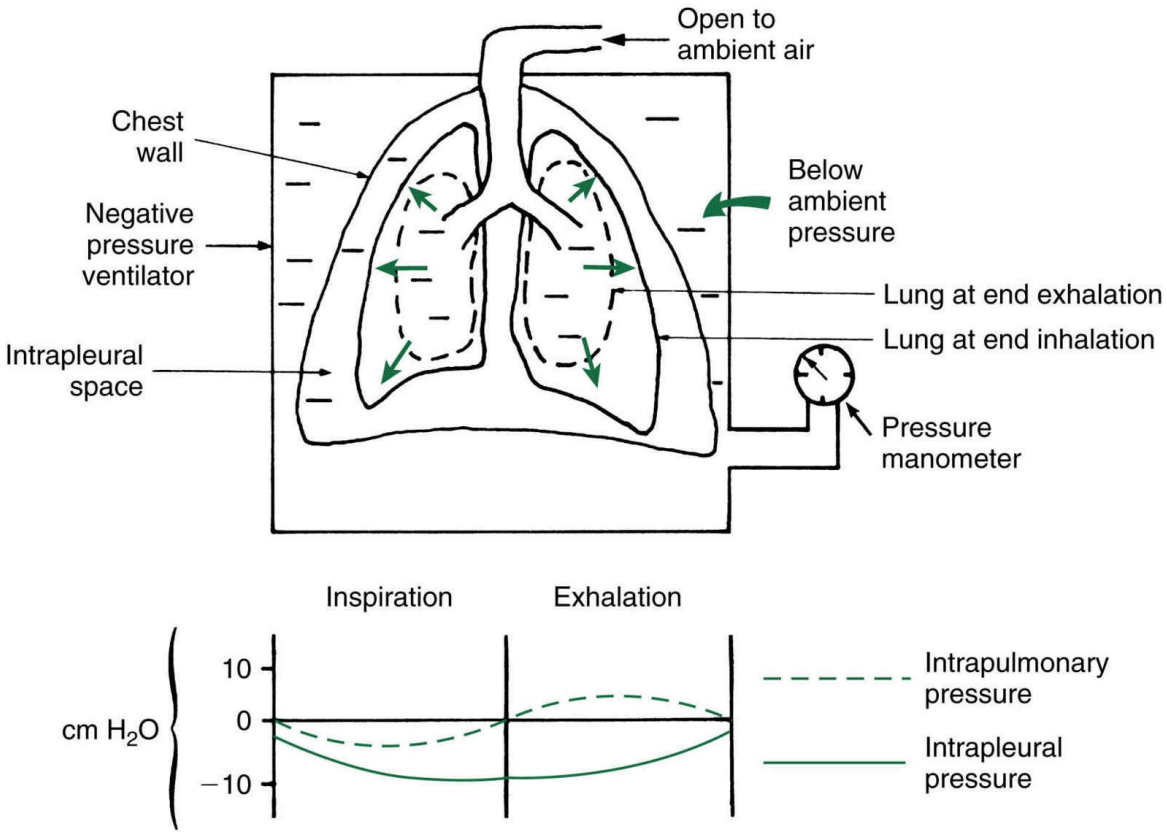

FIG. 1.7 Negative pressure ventilation and the resulting lung mechanics and pressure waves (approximate values). During inspiration, intrapleural pressure drops from about −5 to −10 cm H_2O and alveolar (intrapulmonary) pressure declines from 0 to −5 cm H_2O; as a result, air flows into the lungs. The alveolar pressure returns to zero as the lungs fill. Flow stops when pressure between the mouth and the lungs is equal. During exhalation, intrapleural pressure increases from about −10 to −5 cm H_2O and alveolar (intrapulmonary) pressure increases from 0 to about +5 cm H_2O as the chest wall and lung tissue recoil to their normal resting position; as a result, air flows out of the lungs. The alveolar pressure returns to zero, and flow stops.

Positive Pressure Ventilation

Positive pressure ventilation (PPV) occurs when a mechanical ventilator is used to deliver air into the patient's lungs by way of an endotracheal tube or positive pressure mask. For example, if the pressure 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. There are three types of high-frequency ventilation strategies: **high-frequency positive pressure ventilation** (HFPPV), which uses respiratory rates of about 60 to 100 breaths/min; **high-frequency jet ventilation** (HFJV), which uses rates between about 100 and 400 to 600 breaths/min; and **high-frequency oscillatory ventilation** (HFOV), which uses rates into the thousands, up to about 4000 breaths/min. In clinical practice, the various types of high-frequency ventilation are better defined by the type of ventilator used rather than the specific rates of each.

HFPPV can be accomplished with a conventional positive pressure ventilator set at high rates and lower than normal tidal volumes. HFJV involves delivering pressurized jets of gas into the lungs at very 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. HFOV 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**. Chapters 22 and 23 provide more detail 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 ventilator to determine the airway pressure present at that moment. This reading is measured either very 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 that represents 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.

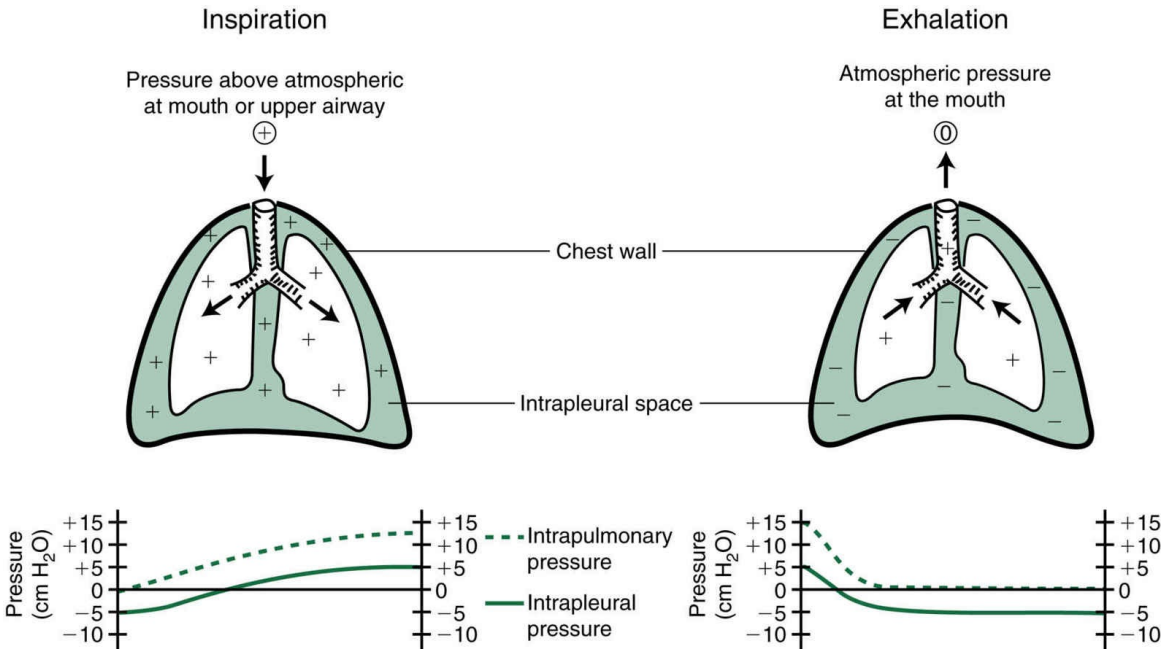

FIG. 1.8 Mechanics and pressure waves associated with positive pressure ventilation. During inspiration, as the upper airway pressure rises to about +15 cm H_2O (not shown), the alveolar (intrapulmonary) pressure is zero; as a result, air flows into the lungs until the alveolar pressure rises to about +9 to +12 cm H_2O. The intrapleural pressure rises from about 5 cm H_2O before inspiration to about +5 cm H_2O 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_2O 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_2O during exhalation.

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.

Sometimes 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, is air that is accidentally trapped in the lung. **Intrinsic PEEP** usually 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 (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 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). Note that the plateau pressure reading will be inaccurate if the patient is actively breathing during the measurement.

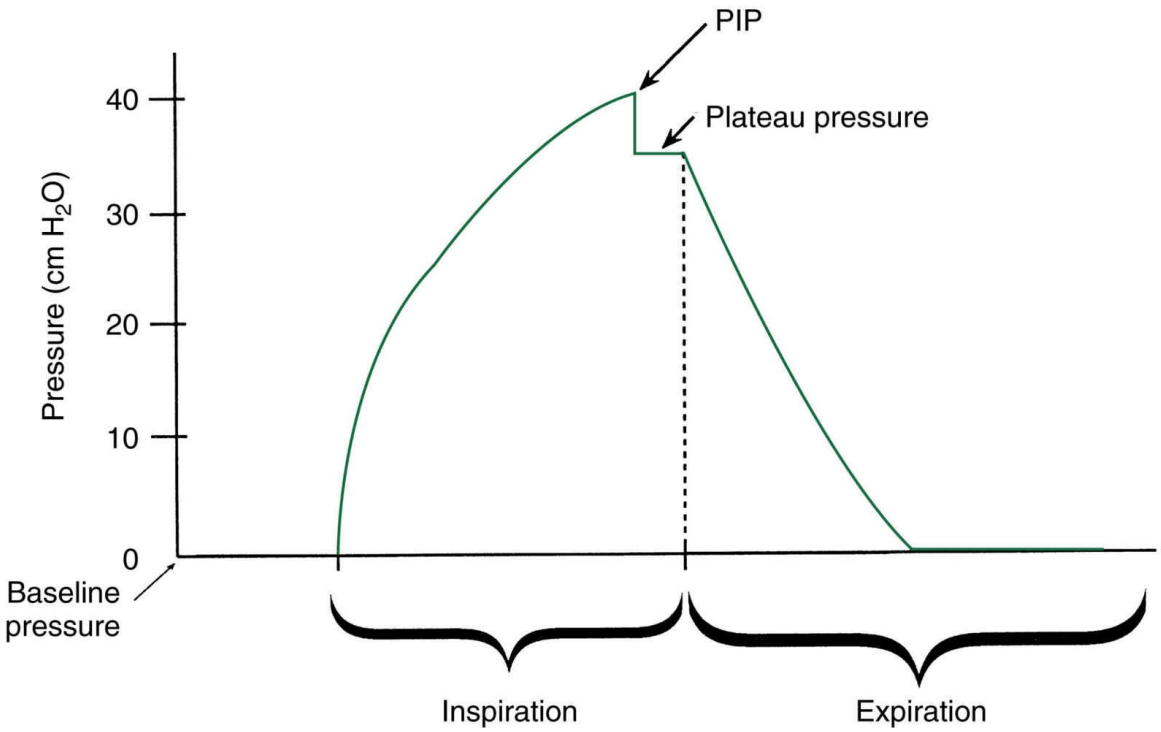

FIG. 1.9 Graph of upper-airway pressures that occur during a positive pressure breath. Pressure rises during inspiration to the peak inspiratory pressure (PIP). With a breath hold, the plateau pressure can be measured. Pressures fall back to baseline during expiration.

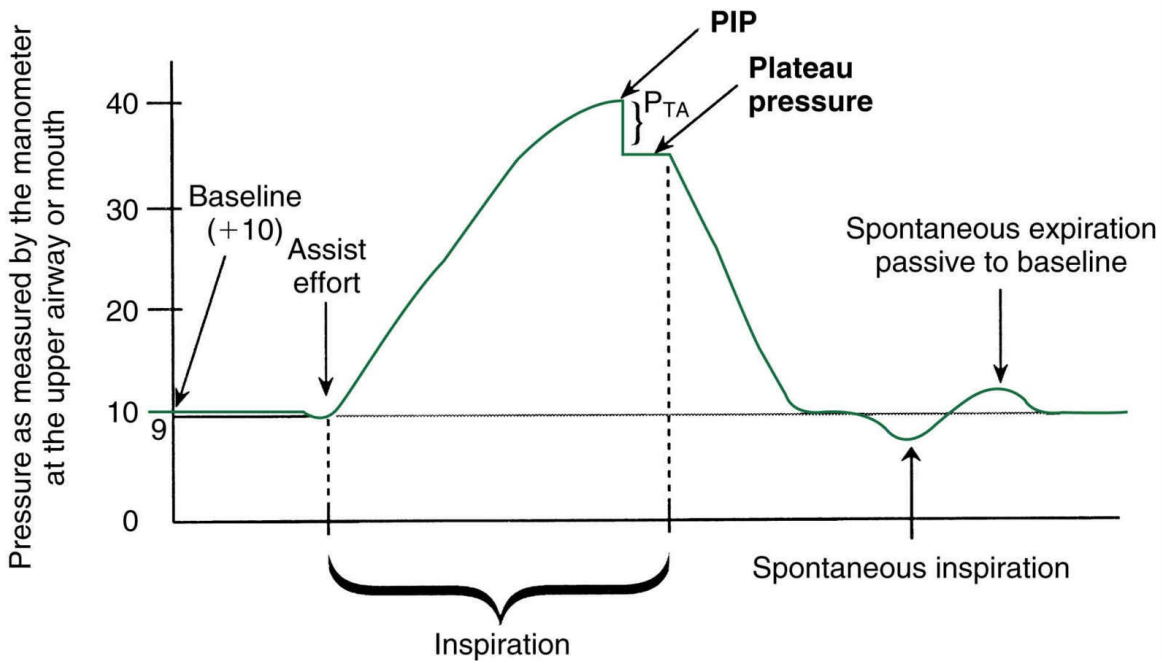

FIG. 1.10 Graph of airway pressures that occur during a mechanical positive pressure breath and a spontaneous breath. Both show an elevated baseline (positive end-expiratory pressure [PEEP] is +10 cm H_2O). To assist a breath, the ventilator drops the pressure below baseline by 1 cm H_2O. The assist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

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 upon 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 not enough time is allowed for exhalation. The most effective way to prevent this complication is to monitor the pressure in the ventilator circuit at the end of exhalation. If no extrinsic PEEP is 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).

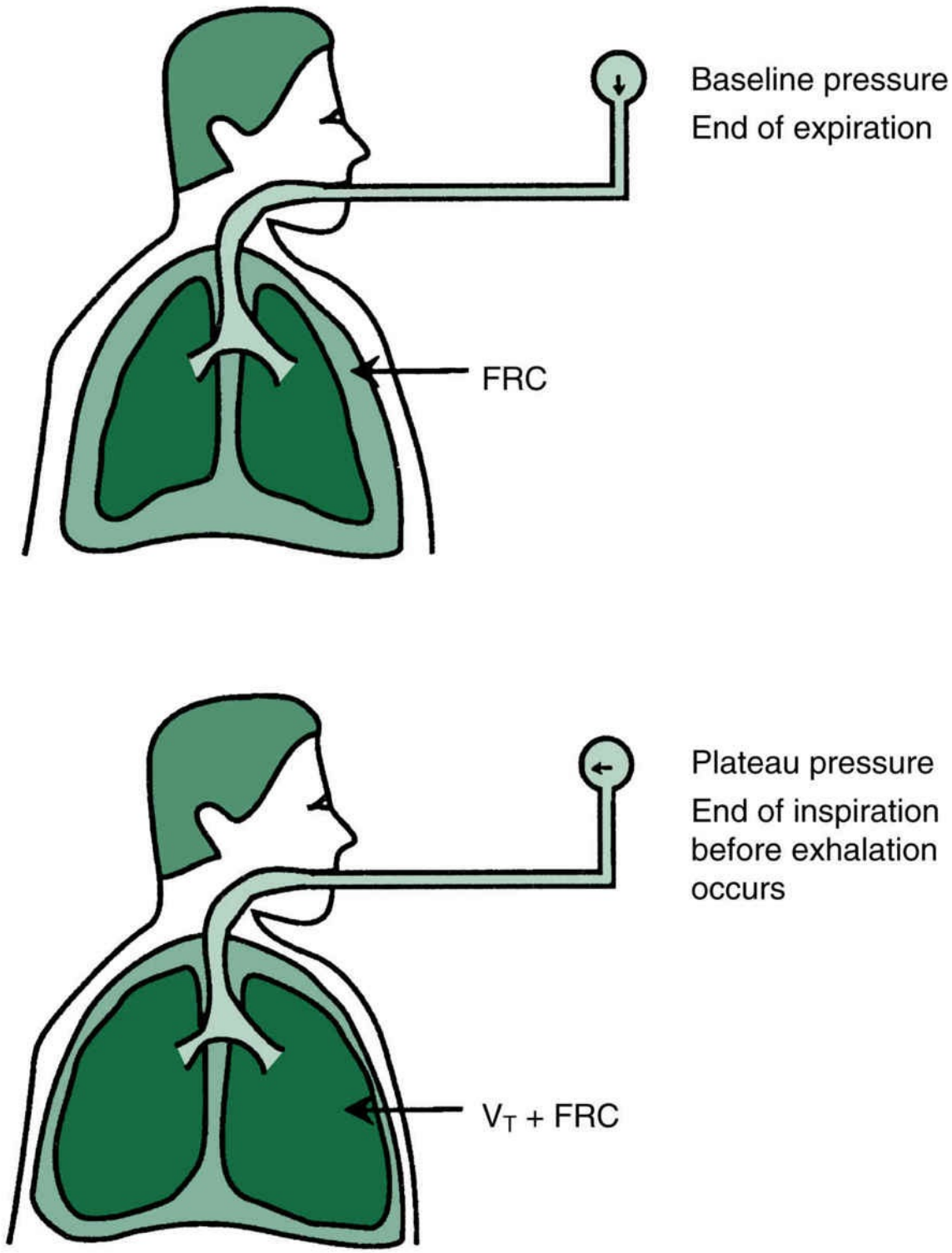

FIG. 1.11 At baseline pressure (end of exhalation), the volume of air remaining in the lungs is the functional residual capacity (FRC). At the end of inspiration, before exhalation starts, the volume of air in the lungs is the tidal volume (V_T) plus the FRC. The pressure measured at this point, with 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, the gas density, the length and diameter of the tube, and the 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)

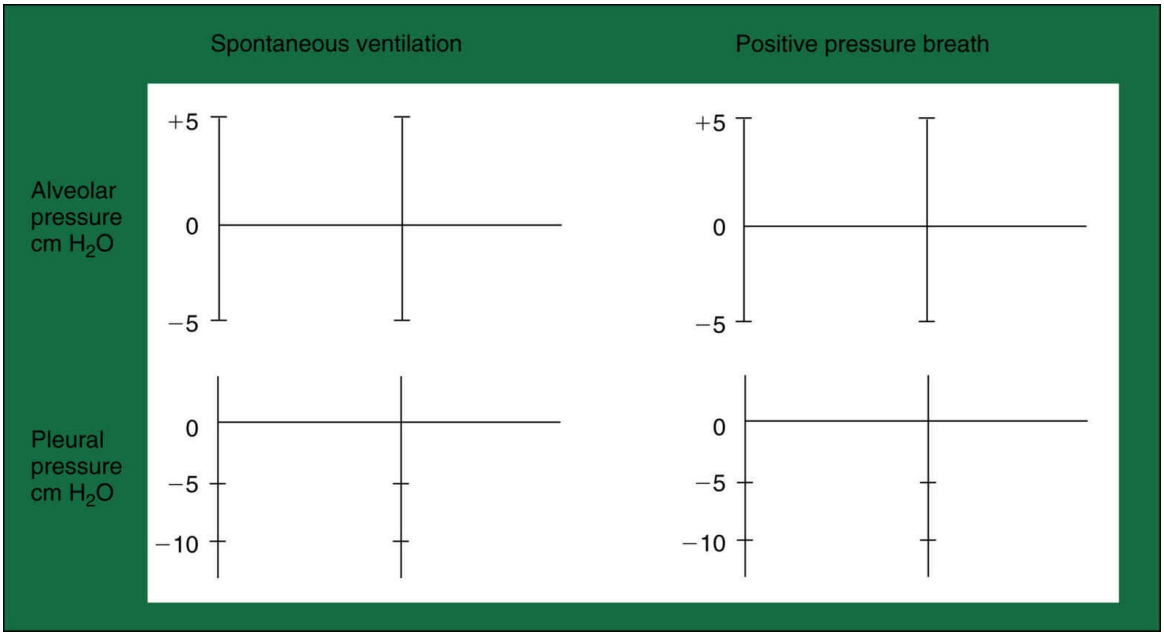

FIG. 1.12 Graphing of alveolar and pleural pressures for spontaneous ventilation and a positive pressure breath.

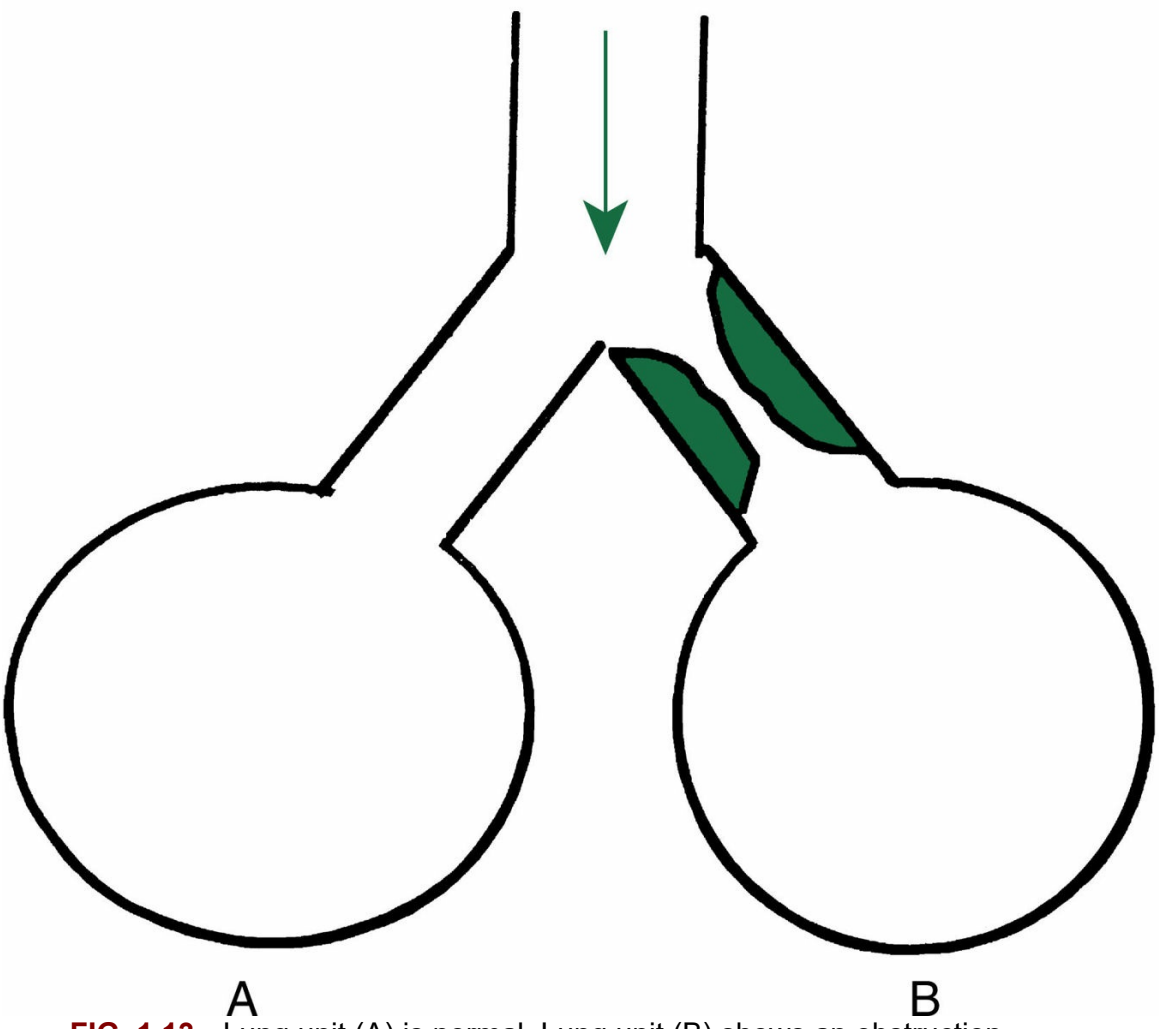

FIG. 1.13 Lung unit (A) is normal. Lung unit (B) shows an obstruction in the airway.

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

8. Define elastance.

A. Ability of a structure to stretch

B. Ability of a structure to return to its natural shape after stretching

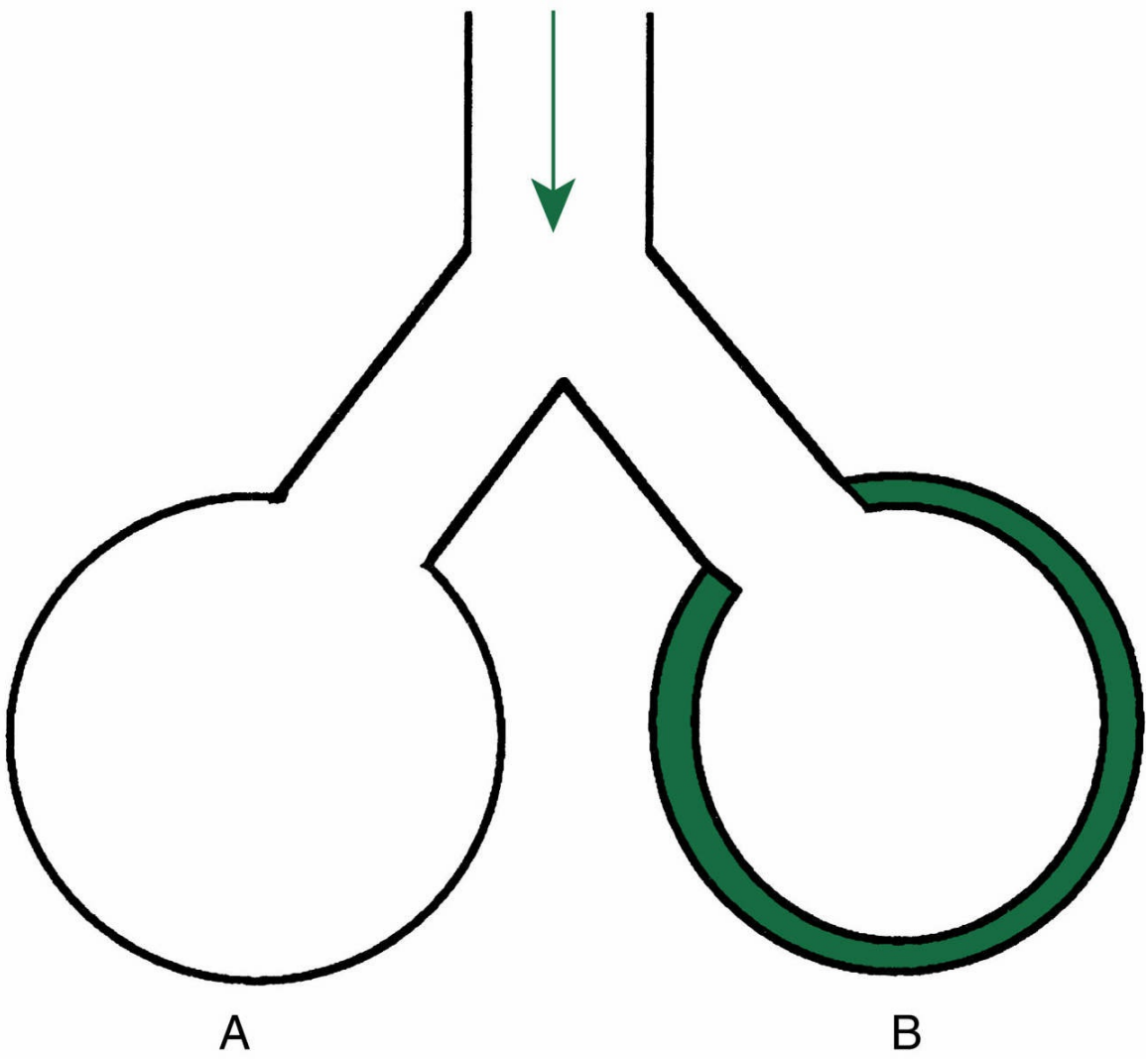

FIG. 1.14 Lung unit (A) is normal. Lung unit (B) shows decreased compliance (see text).

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

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* The definition of transpulmonary pressure varies in research articles and textbooks. Some authors define it as the difference between airway opening pressure and pleural pressure, whereas others define transpulmonary pressure as the pressure difference between airway pressure and pleural pressure. This latter definition implies that airway pressure is the pressure exerted by the lungs during a breath-hold maneuver, that is, under static (no flow) conditions.[4]

* The transairway pressure (P_{TA}) in this equation sometimes is referred to as ?P, the difference between peak inspiratory pressure (PIP) and P_{plat}. (See the section on defining pressures in positive pressure 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]

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

CHAPTER 2

How Ventilators Work

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.

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

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., the Mörch and the Emerson Post-Op) were developed in the 1950s and 1960s. These devices originally were classified 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." It is plugged into an electrical outlet or a high-pressure gas source, and gas comes out the other side. The person who operates the ventilator sets certain dials or a touch panel on a control panel (**user interface**) to establish the pressure and pattern of gas flow delivered by the machine. Inside the black box, 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 [AC] in the United States; higher voltages [220 V, 50 Hz] in other countries), or a rechargeable battery (direct current [DC]) 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 [COPD] patients).

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