

FIFTH EDITION



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ESSENTIALS OF Cardiopulmonary Physical Therapy

Ellen Hillegass



Essentials of Cardiopulmonary Physical Therapy

FIFTH EDITION

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Elsevier 3251 Riverport Lane St. Louis, Missouri 63043

ESSENTIALS OF CARDIOPULMONARY PHYSICAL THERAPY, FIFTH EDITION ISBN: 978-0-32372212-4

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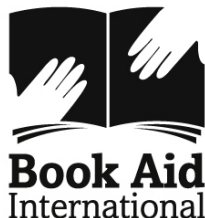
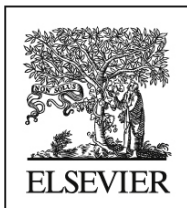
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Library of Congress Control Number: 2021945395

Senior Content Strategist: Lauren Willis *Senior Content Development Manager:* Luke Held *Senior Content Development Specialist:* Maria Broeker *Senior Project Manager:* Umarani Natarajan *Publishing Services Manager:* Shereen Jameel *Senior Book Designer:* Margaret Reid Printed in Canada Last digit is the print number: 987654321



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Dedication

This book is dedicated to my beloved family for all their love and support, as well as their understanding during my endless hours of working on this edition:

To my husband Dan, who is my rock and my biggest supporter whom I could not live without.

To my three wonderful children: Jamie, Christi, and Patrick (and his wife Tiffany) who give me moral support, make me laugh, and who constantly try to keep me up to date on all the modern technologies that have helped me communicate with them, communicate with my colleagues, and write this book! They keep me young with their ideas and assistance and they constantly have a “joie de vivre”; I also need to dedicate this to my three grandchildren: Grae, Grimes, and Brooks, as well as to my future grandchildren. These wonderful children are our future. In addition, my grand dogs give me great pleasure and are part of my full life: Gus, Beans, Darcy, and Roo.

To my dogs: Bear and Ernie (and in loving memory of Sparky) who kept my feet warm while I sat for hours at the computer working on this edition but demanded daily play and provided a wonderful mental break from writing.

And,

In loving memory of my parents, John and Norma Zettler, who kept me busy as their daughter and caregiver while they were alive and were always proud of everything I did.

And, to my brother-in-law George Hillegass, who was an inspiration to everyone he knew and met with his positive attitude and fighting spirit that he had up until the day he died from pancreatic cancer.

In addition, I dedicate this edition:

To my colleagues who keep me informed, give me moral and intellectual support, and who keep me inspired to maintain my passion for the field of cardiovascular and pulmonary physical therapy. I especially rely on the support and inspiration of some very dear friends/colleagues including Angela Campbell, Talia Pollok, Morgan Johanson, Dianne Jewell, Andrew Ries, Claire Rice, and Joanne Watchie.

To my current and all of my former students in DPT programs and from continuing education courses I have presented, as well as my former residents. I have especially enjoyed being a mentor to many rising cardiopulmonary specialists. My former residents will be seen throughout this edition as co-authors and you should expect to see their names as they rise in the profession: Tiffany Haney, Stephen Ramsey, Jenna Floyd Hightower, Liana Geddes, Cydney Nagridge Reilly, Ben Purrington, and Erica Colclough.

And finally, I can never forget my very special friends/mentors to whom I am forever grateful and whose memories and teachings are with me always: Michael Pollock (1937–1998), Linda Crane (1951–1999), and Gary Dudley (1952–2006).

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Preface

Originally, this text was developed to meet the needs of the physical therapy community because cardiopulmonary was identified as one of the four clinical science components in a physical therapy education program, as well as in clinical practice. Those aspects of physical therapy commonly referred to as “cardiovascular and pulmonary physical therapy” are recognized as fundamental components of the knowledge base and practice base of all entry-level physical therapists. Therefore, this text was developed for entry-level physical therapists, as well as individuals in practice who need more in-depth knowledge of cardiopulmonary content. This text is also used by many clinicians studying for advanced practice board certification, in addition to those involved in residency programs. Although intended primarily for physical therapists, this text has been useful to practitioners in various disciplines who teach students or who work with patients suffering from primary and secondary cardiopulmonary dysfunction. This fifth edition can also be used by all practitioners who teach entry-level clinicians, work with residents, as well as to help in clinical practice of patients with cardiopulmonary dysfunction.

This fifth edition has gone through update and revision from the fourth edition to make the text more user friendly and provide more interactive learning. The same six sections exist: *Anatomy and Physiology*; *Pathophysiology*; *Diagnostic Tests and Procedures*; *Surgical Interventions, Monitoring, and Support*; *Pharmacology*; and *Cardiopulmonary Assessment and Intervention*. The six sections were maintained because they facilitate the progression of understanding of the material to be able to perform a thorough assessment and provide an optimal intervention, as well as provide measurable outcomes to assess change.

The revisions you should notice include both major and minor changes. Two NEW chapters were added: [Chapter 4](#), *Management of Cardiovascular Disease in Women* and [Chapter 8](#), *Pulmonary Vascular Disease*. Both are very much needed for understanding these special topics in cardiopulmonary disease, and I celebrate their addition!

All chapters have been revised and supplemented with many updated figures and tables; there are also some videos to help the learner visualize the written information. Additional figures, case studies, and resource material can also be found on the Evolve website that accompanies this text. The number of clinical notes was increased to help clinicians and students understand certain clinical findings and help them relate them to the pathophysiology of cardiovascular and pulmonary disease. All chapters were updated with new information, technology, and research.

Each chapter had specific revisions that should be highlighted. [Chapters 1 and 2](#), which explain anatomy and physiology, increased the number of figures to help the learner relate the pathophysiology to the normal anatomy and physiology. [Chapter 3](#), *Ischemic Cardiovascular Conditions and Other Vascular Pathologies*, underwent revision particularly in areas that were lacking such as venous dysfunction including deep vein thrombosis. New material was added, so that you will now find hypertension, peripheral arterial disease, cerebrovascular disease, renal disease, and aortic aneurysm in this chapter, in addition to ischemic disease. [Chapter 5](#), *Cardiac Muscle Dysfunction and Failure*, was restructured and revised to improve the flow and understanding of this important pathologic condition, as well as all new figures and tables to help understand heart dysfunction and failure.

Because of the complexities and number of conditions of restrictive lung dysfunction, many more tables were created in [Chapter 6](#) to separate the material and assist the learner to identify key information quickly. [Chapter 7](#), *Chronic Obstructive Pulmonary Diseases*, was updated and revised to emphasize the importance of this disease and the fact that COPD is the third leading cause of death. Revisions in [Chapter 9](#), *Cardiopulmonary Implications of Specific Diseases*, emphasize information on obesity, diabetes, and metabolic syndrome, as well as cancer and neuromuscular diseases.

New technologies and advancements in diagnostic tests and surgical procedures were added to [Chapters 10, 11, 12, and 13](#). [Chapter 13](#), *Cardiovascular and Thoracic Interventions*, underwent revision with many new figures and text. The advances in transplantation were discussed in [Chapter 14](#) and monitoring

and life support ([Chapter 15](#)) was revised to increase the depth of information on ventilators, as well as other monitoring equipment found in intensive care units and used by Physical Therapists when mobilizing patients earlier.

As advances in healthcare and diagnostics occur, so do improvements and changes in medications, so both *Cardiovascular Medications* ([Chapter 16](#)) and *Pulmonary Medications* ([Chapter 17](#)) required updating. [Chapter 18](#), *Examination and Assessment Procedures*, was revised with the addition of new tables to help organize assessments and improve the understanding of this material. [Chapter 19](#), *Interventions for Acute Cardiopulmonary Conditions*, added a greater emphasis on early mobility and [Chapter 20](#), *Interventions and Prevention Measures for Individuals With Cardiovascular Disease, or Risk of Disease* had major updating and revision, new clinical notes, and many new figures and tables. [Chapter 21](#), *Pulmonary Rehabilitation* was revised to correspond with changes in the new pulmonary rehabilitation (PR) definition and in the changing practice since Medicare revised payment for PR. [Chapter 22](#), *Pediatric Cardiopulmonary Physical Therapy* and [Chapter 23](#), the outcomes chapter was totally revamped and provides great information for measurement of improvement in the cardiopulmonary patient population. Finally, [Chapter 24](#), *The Lymphatic System* underwent update and revision.

Whenever possible, case studies are provided to exemplify the material being presented. Additional case studies are found on Evolve.

No matter how well you understand the material in this book, it will not make you a master clinician, skilled in the assessment and treatment of cardiovascular and pulmonary disorders. To become even a minimally competent clinician, you will have to practice physical therapy under the tutelage of an experienced clinician. *Essentials of Cardiopulmonary Physical Therapy* cannot provide you with everything there is to know about the assessment and treatment of cardiovascular and pulmonary disorders. It will provide the essentials as the title indicates. Learning is a continuous process, and technology and treatment are forever improving; therefore, this text provides clinicians, as well as educators, with the most current information at the time of publication.

It is my true hope that you appreciate this edition and are able to learn from all the wealth of information provided by such wonderful contributors. Without heart and breath there is no therapy!

Acknowledgments

“Change is good and change equals opportunity!” This statement explains how I have approached each edition, but most especially this edition! Hopefully, you will gain knowledge and insight from all the changes as there are many excellent contributions from my colleagues, who are THE experts in cardiovascular and pulmonary physical therapy and who poured their passion into their chapters. This edition is what I consider the “Mentoring” edition.... Many of the co-authors in the chapters are newly recognized cardiopulmonary specialists and past Residents of Cardiopulmonary Residency programs and new to writing. They were mentored along the way, and what they provided to this edition was amazing content, figures, videos, and updated material that makes this text stand out. We can all learn from these experts and you will as you dig into the material in the following pages.

This edition was written and published during COVID-19, so of course there are sections throughout the text discussing COVID-19. Speaking of change... COVID-19 has certainly made our lives different and changed everything we do! But, now more than ever, we need to understand the cardiovascular and pulmonary system and evaluate our patients for risk for, or presence of, dysfunction in these important systems!

Learning does not stop with this text. Continuing education is a vital component of lifelong learning so I would also encourage all of my readers to continue their lifelong learning in cardiopulmonary physical therapy by using always updated webinars from PT Cardiopulmonary Educators from their website: www.ptcardioed.com.

During the publication phase of the first edition of the *Essentials of Cardiopulmonary Physical Therapy*, I was always worried about new developments in the field of cardiovascular and pulmonary diagnosis and treatment that were not going to be covered in the book. My very first editor, Margaret Biblis, kept saying “that’s what the next edition is for” and that is how I approached the second edition and again the third and fourth edition and now this edition. I have saved comments and suggestions along the way, as well as attended conferences regularly to stay current with new developments in the field. And, with the age of the internet, you have access to the new Evolve site that accompanies this text. Instructional material including PowerPoint presentations and a test bank is available to instructors in the course, as well as updated information.

So, I would like to thank all the amazing experts who have helped with this fifth edition, including each of the wonderful contributors, as well as all those clinicians, students, and faculty members who provided feedback on previous editions and who continue to use this book in their courses and their everyday practice. I would like to especially thank the contributors for their ability to work under my constant nagging to achieve their deadlines and for providing great material including figures, tables, and clinical notes.

Of course, my family and my dogs need to be acknowledged for all the time I spent at the computer working on this edition instead of spending time with them.

Lastly, this edition truly would not be published were it not for my wonderful editor, Maria Broeker. Thanks, Maria!

SECTION 1

Anatomy and Physiology

OUTLINE

-
1. Anatomy of the cardiovascular and pulmonary systems
 2. Physiology of the cardiovascular and pulmonary systems

1: Anatomy of the cardiovascular and pulmonary systems

Konrad J. Dias, and Germaine Ferreira

CHAPTER OUTLINE

- Thorax
 - Sternum
 - Ribs
- The respiratory system
 - Muscles of ventilation
 - Muscles of expiration
 - Pulmonary ventilation
- The cardiovascular system
 - Mediastinum
 - Heart
 - Innervation
- Cardiac and pulmonary vessels
 - Aorta
 - Right coronary artery
 - Left coronary artery
 - Pulmonary artery
 - Pulmonary veins
 - Vena cava and cardiac veins
- Systemic circulation
 - Arteries
 - Endothelium
 - Veins
- Summary
- References

This chapter describes the anatomy of the cardiovascular and pulmonary systems because it is relevant to the physical therapist. Knowledge of the anatomy of these systems provides clinicians with the foundation to perform the appropriate examination and provide optimal treatment interventions for individuals with cardiopulmonary dysfunction. An effective understanding of cardiovascular and pulmonary anatomy allows for comprehension of function and an appreciation of the central components of oxygen and nutrient transport to peripheral tissue. A fundamental assumption is made; namely, that the reader already possesses some knowledge of anatomic terms and cardiopulmonary anatomy.

Thorax

The bony thorax covers and protects the major organs of the cardiopulmonary system. Within the thoracic cavity exists the heart, housed within the mediastinum centrally, and laterally are two lungs. The bony thorax provides a skeletal framework for the attachment of the muscles of ventilation.

The thoracic cage ([Fig. 1.1](#)) is conical at both its superior and inferior aspects and somewhat kidney shaped in its transverse aspect. The skeletal boundaries of the thorax are the 12 thoracic vertebrae dorsally, the ribs laterally, and the sternum ventrally.

Sternum

The sternum, or breastbone, is a flat bone with three major parts: manubrium, body, and xiphoid process (see [Fig. 1.1](#)). Superiorly located within the sternum, the manubrium is the thickest component articulating with the clavicles and first and second ribs. A palpable jugular notch or suprasternal notch is found at the superior border of the manubrium of the sternum. Inferior to the manubrium lies the body of the sternum, articulating laterally with ribs three to seven. The sternal angle, or “angle of Louis,” is the anterior angle formed by the junction of the manubrium and the body of the sternum. This easily palpated structure is in level with the second costal cartilage anteriorly and thoracic vertebrae T4 and T5 posteriorly. The most caudal aspect of the sternum is the xiphoid process, a plate of hyaline cartilage that ossifies later in life.

The sternal angle marks the level of bifurcation of the trachea into the right and left main stem bronchi and provides for the pump-handle action of the sternal body during inspiration. ¹

Pectus excavatum is a common congenital deformity of the anterior wall of the chest in which several ribs and the sternum grow abnormally (see [Fig. 5.25](#)). This produces a caved-in or sunken appearance of the chest. It is present at birth, but rapidly progresses during the years of bone growth in the early teenage years. These patients have several pulmonary complications, including shortness of breath caused by altered mechanics of the inspiratory muscles on the caved-in sternum and ribs, and often have cardiac complications caused by the restriction (compression) of the heart. ²

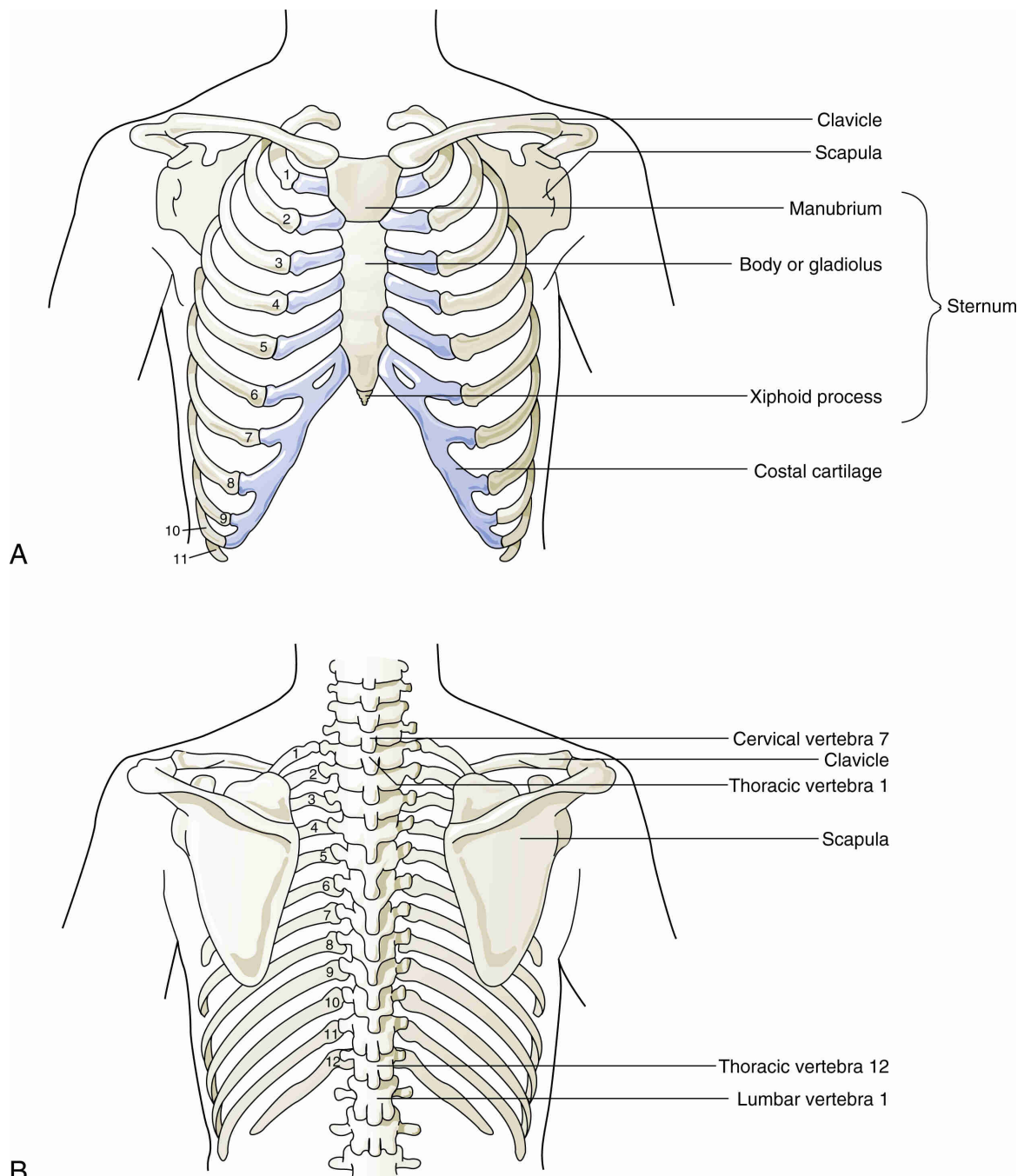


FIGURE 1.1 (A) Anterior. (B) Posterior views of the bones of the thorax.

From Hicks GH: *Cardiopulmonary anatomy and physiology*, Philadelphia, 2000, Saunders.

To gain access to the thoracic cavity for surgery, including coronary artery bypass grafting, the sternum is split in the median plane and retracted. This procedure is known as a median sternotomy. Flexibility of the ribs and cartilage allows for separation of the two ends of the sternum to expose the thoracic cavity.³

Ribs

The ribs, although considered “flat” bones, curve forward and downward from their posterior vertebral attachments toward their costal cartilages. The first seven ribs attach via their costal cartilages to the sternum and are called the true ribs (also known as the vertebrosteral ribs); the lower five ribs are termed the false ribs—the 8th, 9th, and 10th ribs attach to the rib above by their costal cartilages (the vertebrochondral ribs), and the 11th and 12th ribs end freely (the vertebral ribs; see Fig. 1.1). The true ribs increase in length from above downward, and the false ribs decrease in length from above downward.

Each rib typically has a vertebral end separated from a sternal end by the body or shaft of the rib. The head of the rib (at its vertebral end) is distinguished by a twin-faceted surface for articulation with the facets on the bodies of two adjacent thoracic vertebrae. The cranial facet is smaller than the caudal, and a crest between these permits attachment of the interarticular ligament.

Fig. 1.2 displays the components of typical ribs 3 to 9, each with common characteristics, including a head, neck, tubercle, and body. The neck is the 1-inch long portion of the rib extending laterally from the head; it provides attachment for the anterior costotransverse ligament along its cranial border. The tubercle at the junction of the neck and the body of the rib consists of an articular and a nonarticular portion. The articular part of the tubercle (the more medial and inferior of the two) has a facet for articulation with the transverse process of the inferior-most vertebra to which the head is connected. The nonarticular part of the tubercle provides attachment for the ligament of the tubercle.

The shaft, or body, of the rib is simultaneously bent in two directions and twisted about its long axis, presenting two surfaces (internal and external) and two borders (superior and inferior). A costal groove for the intercostal vessels and nerve extends along the inferior border dorsally but changes to the internal surface at the angle of the rib. The sternal end of the rib terminates in an oval depression into which the costal cartilage makes its attachment.

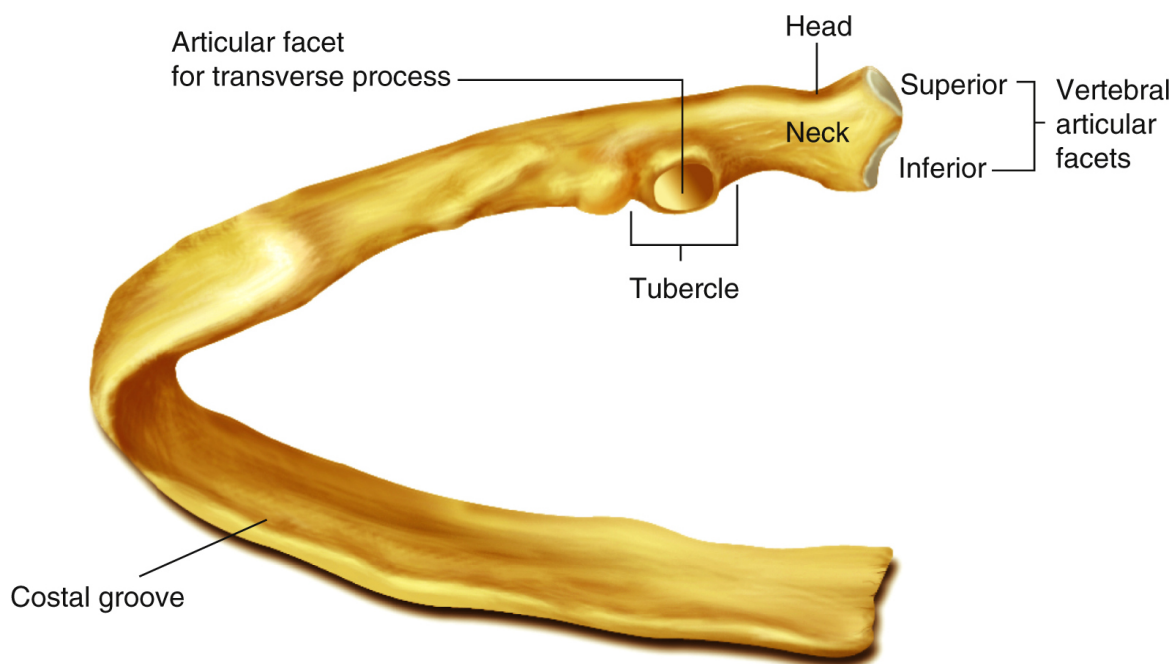


FIGURE 1.2 Typical middle rib as viewed from the posterior. The head end articulates with the vertebral bones, and the distal end is attached to the costal cartilage of the sternum.

From Wilkins RL: *Egan's fundamentals of respiratory care*, ed 9, St. Louis, 2009, Mosby.

Although rib fractures may occur in various locations, they are more common in the weakest area where the shaft of the ribs bend—the area just anterior to its angle. The first rib does not usually fracture because it is protected posteroinferiorly by the clavicle. When it is injured, the brachial plexus of nerves and subclavian vessel injury may occur.⁴ Lower rib fractures may cause trauma to the diaphragm resulting in a diaphragmatic hernia. Rib fractures are extremely painful because of their profound nerve supply. It is important for all therapists to recommend breathing, splinting, and coughing strategies for patients with rib fractures. Paradoxical breathing patterns and a flail chest may also need to be evaluated in light of multiple rib fractures in adjacent ribs.³

Chest tubes are inserted above the ribs to avoid trauma to vessels and nerves found within the costal groove. A chest tube insertion involves the surgical placement of a hollow, flexible drainage tube into the chest. This tube is used to drain blood, air, or fluid around the lungs and effectively allow the lung to

expand. The tube is placed between the ribs and into the space between the inner lining and the outer lining of the lung (pleural space).

The 1st, 2nd, 10th, 11th, and 12th ribs are unlike the other, more typical ribs. The first rib is the shortest and most curved of all the ribs. Its head is small and rounded and has only one facet for articulation with the body of the first thoracic vertebra. The sternal end of the first rib is larger and thicker than it is in any of the other ribs. The second rib, although longer than the first, is similarly curved. The body is not twisted. There is a short costal groove on its internal surface posteriorly. The 10th through 12th ribs each have only one articular facet on their heads. The 11th and 12th ribs (floating ribs) have no necks or tubercles and are narrowed at their free anterior ends. The 12th rib sometimes is shorter than the first rib.

The respiratory system

The respiratory system includes the bony thorax, the muscles of ventilation, the upper and the lower airways, and the pulmonary circulation. The many functions of the respiratory system include gas exchange, fluid exchange, maintenance of a relatively low-volume blood reservoir, filtration, and metabolism, and they necessitate an intimate and exquisite interaction of these various components. Because the thorax has already been discussed, this section deals with the muscles of ventilation, the upper and lower airways, and the pulmonary circulation.

Muscles of ventilation

Ventilation, or breathing, involves the processes of inspiration and expiration. For air to enter the lungs during inspiration, muscles of the thoracic cage and abdomen must move the bony thorax to create changes in volume within the thorax and cause a concomitant reduction in the intrathoracic pressure. Inspiratory muscles increase the volume of the thoracic cavity by producing bucket-handle and pump-handle movements of the ribs and sternum, as depicted in [Fig. 1.3](#). The resultant reduced intrathoracic pressure generated is below atmospheric pressure, forcing air into the lungs to help normalize pressure differences. The essential muscles to achieve the active process of inspiration at rest are the diaphragm and internal intercostals. To create a more forceful inspiration during exercise or cardiopulmonary distress, accessory muscles assist with the inspiration. The accessory muscles include the sternocleidomastoid, scalenes, serratus anterior, pectoralis major and minor, trapezius, and erector spinae muscles.

Diaphragm

The diaphragm is the major muscle of inspiration. It is a musculotendinous dome that forms the floor of the thorax and separates the thoracic and abdominal cavities ([Fig. 1.4](#)). The diaphragm is divided into right and left hemidiaphragms. Both hemidiaphragms are visible on radiographic studies from the front or back. The right hemidiaphragm is protected by the liver and is stronger than the left. The left hemidiaphragm is more often subject to rupture and hernia, usually because of weaknesses at the points of embryologic fusion. Each hemidiaphragm is composed of three musculoskeletal components, including the sternal, costal, and lumbar portions that converge into the central tendon. The central tendon of the diaphragm is a thin but strong layer of tendons (aponeurosis) situated anteriorly and immediately below the pericardium. There are three major openings to enable various vessels to traverse the diaphragm. These include the vena caval opening for the inferior vena cava; the esophageal opening for the esophagus and gastric vessels; and the aortic opening containing the aorta, thoracic duct, and azygos veins. The phrenic nerve arises from the third, fourth, and fifth cervical spinal nerves (C3–C5) and is involved in contraction of the diaphragm.

The resting position of the diaphragm is an arched position high in the thorax. The level of the diaphragm and the amount of movement during inspiration vary as a result of factors such as body position, obesity, and size of various gastrointestinal organs present below the diaphragm. During normal ventilation or breathing, the diaphragm contracts to pull the central tendon down and forward. In doing so, the resting dome shape of the diaphragm is reversed to a flattening of the diaphragm. Contraction of this muscle increases the dimensions of the thorax in a cephalocaudal, anterior posterior, and lateral direction.¹ The increase in volume decreases pressure in the thoracic cavity and simultaneously causes a decrease in volume and an increase in pressure within the abdominal cavity. The domed shape of the diaphragm is largely maintained until the abdominal muscles end their extensibility, halting the downward displacement of the abdominal viscera, essentially forming a fixed platform beneath the central tendon. The central

tendon then becomes a fixed point against which the muscular fibers of the diaphragm contract to elevate the lower ribs and thereby push the sternum and upper ribs forward. The right hemidiaphragm meets more resistance than the left during its descent, because the liver underlies the right hemidiaphragm and the stomach underlies the left; it is therefore more substantial than the left.

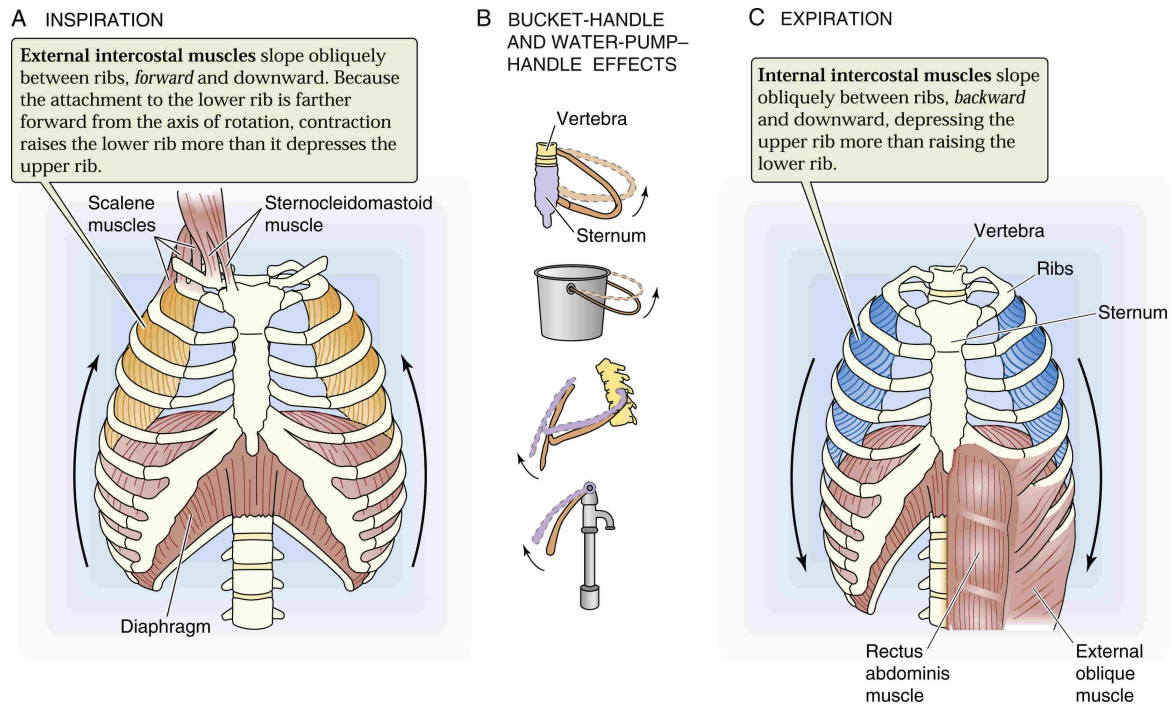


FIGURE 1.3 (A–C) Actions of major respiratory muscles.

From Boron WF: *Medical physiology*, updated ed, St. Louis, 2005, Saunders.

In patients with chronic obstructive pulmonary disease (COPD), there is compromised ability to expire. This results in a flattening of the diaphragm as a result of the presence of hyperinflated lungs.^{1, 5} It is essential for therapists to reverse hyperinflation and restore the normal resting arched position of the diaphragm using any exercise aimed at strengthening the diaphragm muscle. A flat and rigid diaphragm cannot be strengthened and will cause an automatic firing of the accessory muscles to trigger inspiration.

Body position in supine, upright, or side lying alters the resting position of the diaphragm, resulting in concomitant changes in lung volumes.⁶ In the supine position, without the effects of gravity, the level of the diaphragm in the thoracic cavity rises. This allows for a relatively greater excursion of the diaphragm. Despite a greater range of movement of the diaphragm, lung volumes are low as a consequence of the elevated position of the abdominal organs within the thoracic cavity. In an upright position, the dome of the diaphragm is pulled down because of the effects of gravity. The respiratory excursion is less in this position; however, the lung volumes are larger. In the side-lying position, the hemidiaphragms are unequal in their positions: the uppermost side drops to a lower level and has less excursion than that in the sitting position; the lowermost side rises higher in the thorax and has a greater excursion than in the sitting position. In quiet breathing, the diaphragm normally moves about two-thirds of an inch; with maximal ventilatory effort, the diaphragm may move from 2.5 to 4 inches.⁵

Clinical tip

Stomach fullness, obesity with presence of a large pannus, ascites with increased fluid in the peritoneal space from liver disease, and pregnancy are additional factors affecting the normal excursion of the diaphragm during inspiration.

External intercostal muscles

The external intercostal muscles originate from the lower borders of the ribs and attach to the upper border of the ribs below (Fig. 1.5). There are 11 external intercostal muscles on each side of the sternum. Contraction of these muscles pull the lower rib up and out toward the upper rib, thereby elevating the ribs and expanding the chest.

Accessory muscles

Figs. 1.6 and 1.7 present the anatomy of the accessory muscles.

Sternocleidomastoid muscle

The sternocleidomastoid arises by two heads (sternal and clavicular from the medial part of the clavicle), which unite to extend obliquely upward and laterally across the neck to the mastoid process. For this muscle to facilitate inspiration, the head and neck must be held stable by the neck flexors and extensors. This muscle is a primary accessory muscle and elevates the sternum, increasing the anteroposterior diameter of the chest.

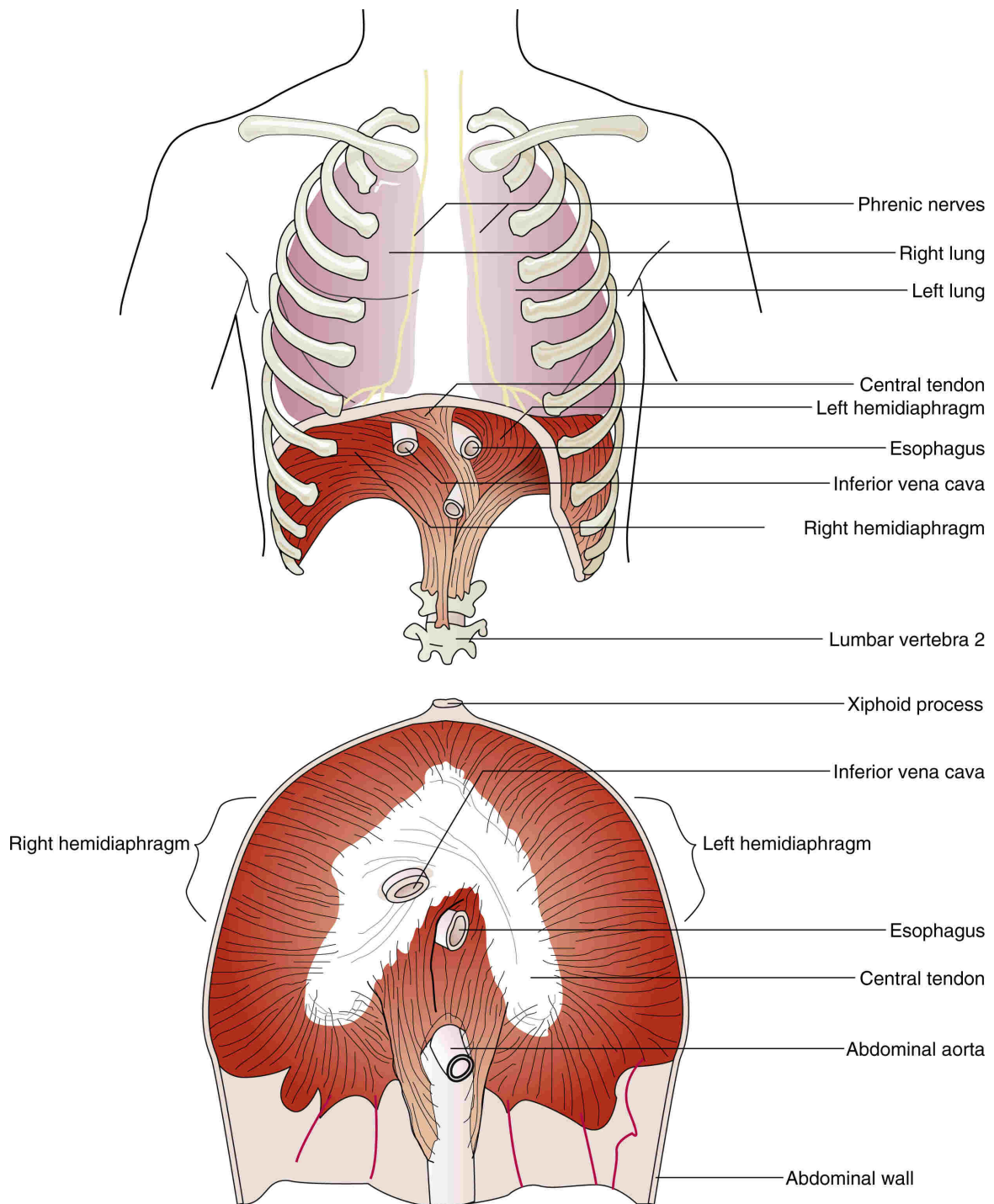


FIGURE 1.4 The diaphragm originates from the lumbar vertebra, lower ribs, xiphoid process, and abdominal wall and converges in a central tendon. Note the locations of the phrenic nerves and openings for the inferior vena cava, esophagus, and abdominal aorta.

From Hicks GH: *Cardiopulmonary anatomy and physiology*, Philadelphia, 2000, Saunders.

Scalene muscle

The scalene muscles lie deep to the sternocleidomastoid, but may be palpated in the posterior triangle of the neck. These muscles function as a unit to elevate and fix the first and second ribs:

1. The anterior scalene muscle passes from the anterior tubercles of the transverse processes of the third or fourth to the sixth cervical vertebrae, attaching by tendinous insertion into the first rib.
2. The middle scalene muscle arises from the transverse processes of all the cervical vertebrae to insert onto the first rib (posteromedially to the anterior scalene, the brachial plexus, and subclavian artery pass between the anterior scalene and middle scalene).
3. The posterior scalene muscle arises from the posterior tubercles of the transverse processes of the fifth and sixth cervical vertebrae, passing between the middle scalene and levator scapulae, to attach onto the second or third rib.

Upper trapezius

The trapezius (upper fibers) muscle arises from the medial part of the superior nuchal line on the occiput and the ligamentum nuchae (from the vertebral spinous processes between the skull and the seventh cervical vertebra) to insert onto the distal third of the clavicle. This muscle assists with ventilation by helping to elevate the thoracic cage.

Pectoralis major and minor

The pectoralis major arises from the medial third of the clavicle, from the lateral part of the anterior surface of the manubrium and body of the sternum, and from the costal cartilages of the first six ribs to insert upon the lateral lip of the crest of the greater tubercle of the humerus. When the arms and shoulders are fixed, by leaning on the elbows or grasping onto a table, the pectoralis major can use its insertion as its origin and pull on the anterior chest wall, lifting the ribs and sternum, and facilitate an increase in the anteroposterior diameter of the thorax.

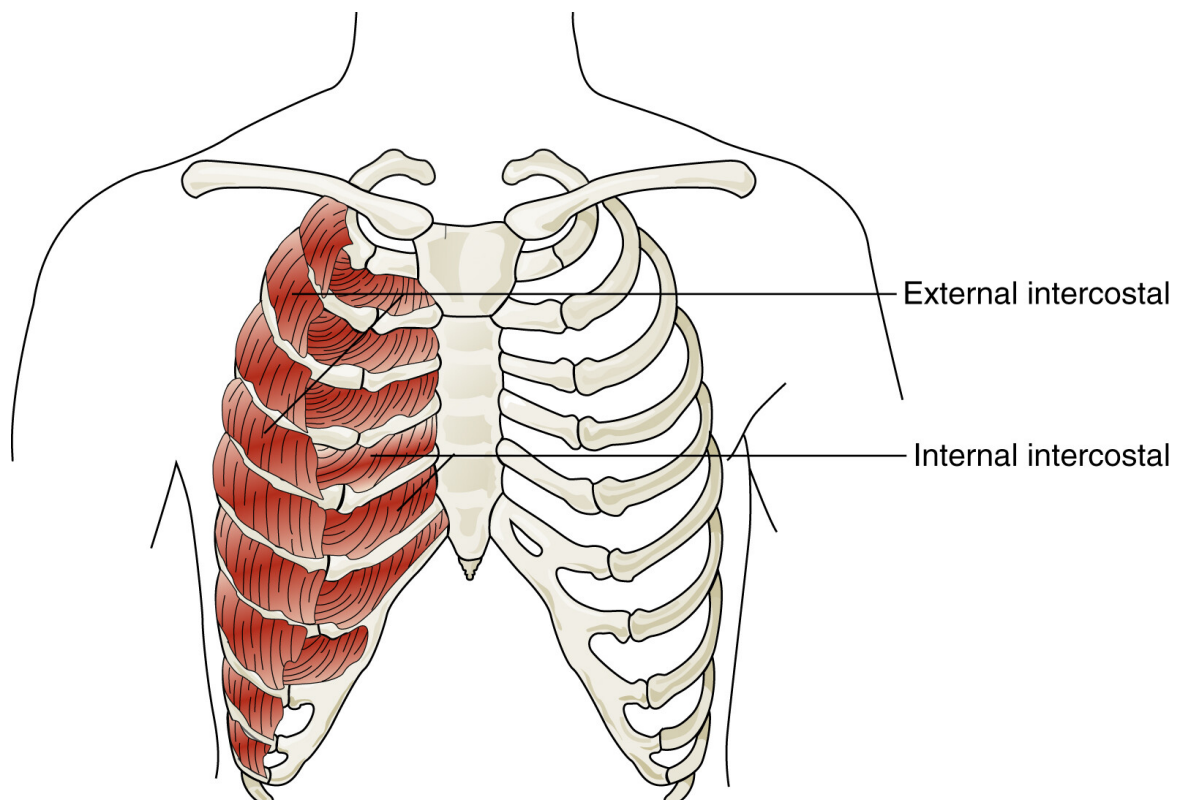


FIGURE 1.5 The external intercostal muscles lift the inferior ribs and enlarge the thoracic cavity. The internal intercostal muscles compress the thoracic cavity by pulling together the ribs.

From Hicks GH: *Cardiopulmonary anatomy and physiology*, Philadelphia, 2000, Saunders.

The pectoralis minor arises from the second to fifth or the third to sixth ribs upward to insert into the medial side of the coracoid process close to the tip. This muscle assists in forced inspiration by raising the ribs and increasing intrathoracic volume.

Serratus anterior and rhomboids

The serratus anterior arises from the outer surfaces of the upper eight or nine ribs to attach along the costal aspect of the medial border of the scapula. The primary action of the serratus is to abduct, rotate the scapula, and hold the medial border firmly over the rib cage. The serratus can only be used as an accessory muscle in ventilation, when the rhomboids stabilize the scapula in adduction.⁷ The action of the rhomboids fixes the insertion, allowing the serratus to expand the rib cage by pulling the origin toward the insertion.

Latissimus dorsi

The latissimus dorsi arises from the spinous processes of the lower six thoracic, the lumbar, and the upper sacral vertebrae, from the posterior aspect of the iliac crest, and slips from the lower three or four ribs to attach to the intertubercular groove of the humerus.⁷ The posterior fibers of this muscle assist in inspiration as they pull the trunk into extension.

Serratus posterior superior

The serratus posterior superior passes from the lower part of the ligamentum nuchae and the spinous processes of the seventh cervical and first two or three thoracic vertebrae downward into the upper borders of the second to fourth or fifth ribs. This muscle assists in inspiration by raising the ribs to which it is attached and expanding the chest.

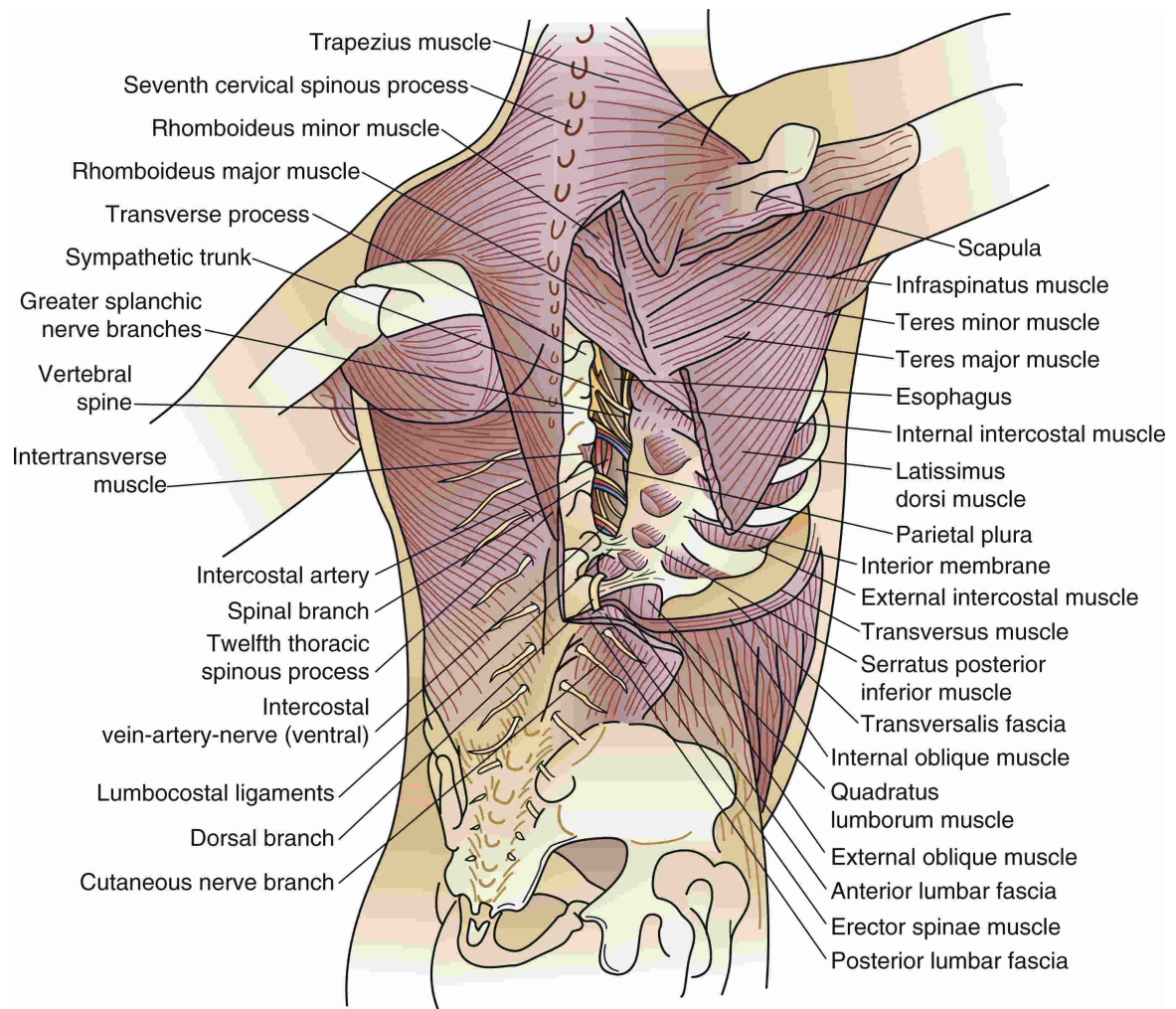


FIGURE 1.6 Musculature of the chest wall.

From Ravitch MM, Steichen FM: *Atlas of general thoracic surgery*, Philadelphia, 1988, Saunders.

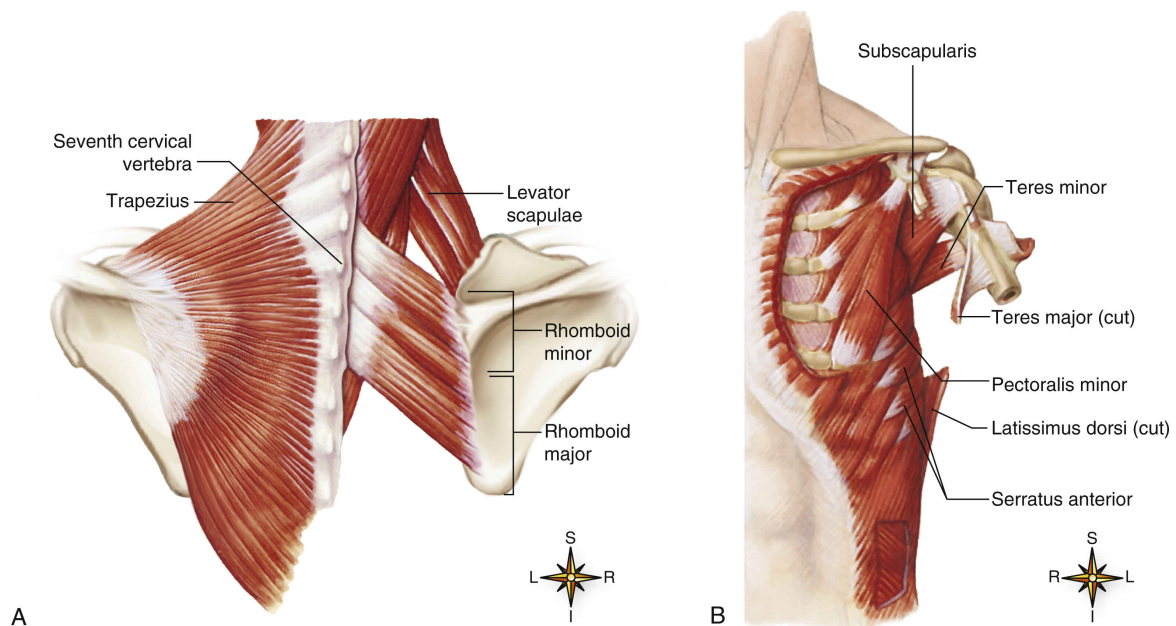


FIGURE 1.7 Musculature of anterior chest wall.

From Patton K, Thibodeau G, Douglas M: *Essentials of anatomy and physiology*, ed 1, St. Louis, 2011, Elsevier.

Thoracic erector spinae muscles

The erector spinae is a large muscle group extending from the sacrum to the skull. The thoracic erector spinae muscles extend the thoracic spine and raise the rib cage to allow greater expansion of the thorax.

Muscles of expiration

Abdominal muscles

The abdominal muscles include the rectus abdominis, transversus abdominis, and internal and external obliques. These muscles work to raise intraabdominal pressure when a sudden expulsion of air is required in maneuvers, such as huffing and coughing. Pressure generated within the abdominal cavity is transmitted to the thoracic cage to assist in emptying the lungs.

Internal intercostal muscles

Eleven internal intercostal muscles exist on each side of the sternum. These muscles arise on the inner surfaces of the ribs and costal cartilages and insert on the upper borders of the adjacent ribs below (see Fig. 1.5). The posterior aspect on the internal intercostal muscles is termed the interosseus portion and depresses the ribs to aid in a forceful expiration. The intercartilaginous portion of the internal intercostals elevates the ribs and assists in inspiration.

Pulmonary ventilation

Pulmonary ventilation, commonly referred to as breathing, is the process in which air is moved in and out of the lungs. Inspiration, an active process at rest and during exercise, involves contraction of the diaphragm and external intercostal muscles. The muscle that contracts first is the diaphragm, with a caudal movement and resultant increase within the volume of the thoracic cavity. The diaphragm eventually meets resistance against the abdominal viscera, causing the costal fibers of the diaphragm to contract and pull the lower ribs up and out—the bucket-handle movement. The outward movement is also facilitated by the external intercostal muscles. In addition, a pump-handle movement of the upper ribs is achieved through contraction of the external intercostals and the intercartilaginous portion of the internal intercostal muscles. The actions of the inspiratory muscles expand the dimensions of the thoracic cavity and concomitantly reduce the pressure in the lungs (intrathoracic pressure) below the air pressure outside the body. With the

respiratory tract being open to the atmosphere, air rushes into the lungs to normalize the pressure difference, allowing inspiration to occur and the lungs to fill with air.

During forced or labored breathing, additional accessory muscles need to be used to increase the inspiratory maneuver. The accessory muscles raise the ribs to a greater extent and promote extension of the thoracic spine. These changes facilitate a further increase in the volume within the thoracic cavity and a subsequent drop in the intrathoracic pressure beyond that caused by the contraction of the diaphragm and external intercostals. This relatively lower intrathoracic pressure will promote a larger volume of air entering the lung.

At rest, expiration is a passive process and achieved through the elastic recoil of the lung and relaxation of the external intercostal and diaphragm muscle. As the external intercostals relax, the rib drops to its preinspiratory position and the diaphragm returns to its elevated dome position high in the thorax. To achieve a forceful expiration, additional muscles can be used, including the abdominals and internal intercostal muscles. The internal intercostals actively pull the ribs down to help expel air out of the lungs. The abdominals contract to force the viscera upward against the diaphragm, accelerating its return to the dome position.

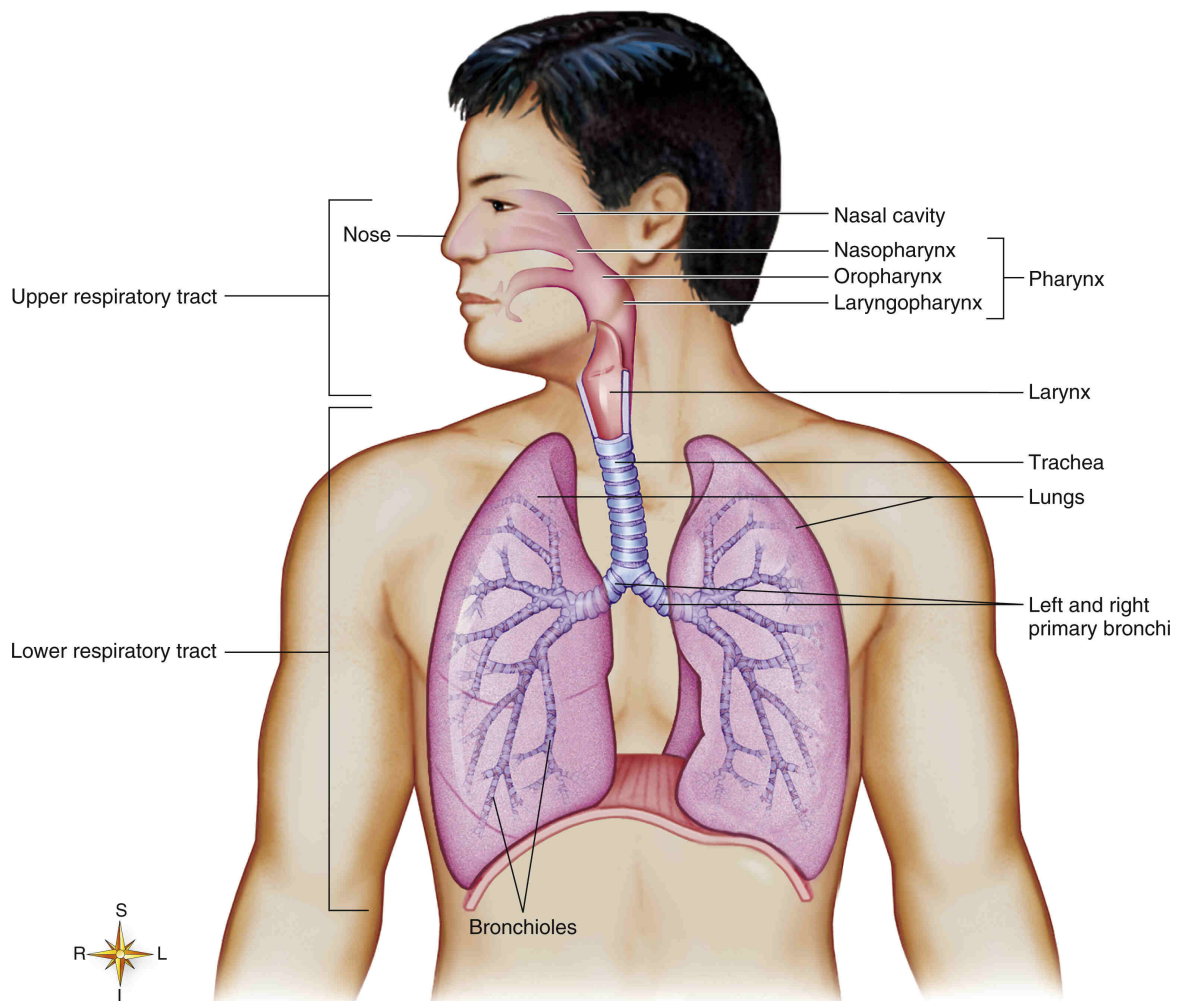


FIGURE 1.8 Pleurae of the lungs.

From Patton K, Thibodeau G, Douglas M: *Essentials of anatomy and physiology*, ed 1, St. Louis, 2011, Elsevier.

Clinical tip

The changes in intraabdominal and intrathoracic pressure that occur with forced breathing assist with venous return of blood back to the heart. The drop in pressure allows for a filling of the veins, and the changing pressure within the abdomen and thorax cause a milking effect to help return blood back to the heart.

Pleurae

Two serous membranes, or pleurae, exist that cover each lung (Fig. 1.8). The pleura covering the outer surface of each lung is the visceral pleura and is inseparable from the tissue of the lung. The pleura covering the inner surface of the chest wall, diaphragm, and mediastinum is called the parietal pleura. The parietal pleura is frequently described with reference to the anatomic surfaces it covers: the portion lining the ribs and vertebrae is named the costovertebral pleura; the portion over the diaphragm is the diaphragmatic pleura; the portion covering the uppermost aspect of the lung in the neck is the cervical pleura; and that overlying the mediastinum is called the mediastinal pleura.⁸ Parietal and visceral pleurae blend with one another where they come together to enclose the root of the lung. Normally, the pleurae are in intimate contact during all phases of the ventilatory cycle, being separated only by a thin serous film. There exists a potential space between the pleurae called the pleural space or pleural cavity. A constant negative pressure within this space maintains lung inflation. The serous fluid within the pleural space serves to hold the pleural layers together during ventilation and reduce friction between the lungs and the thoracic wall.^{6, 8}

The parietal pleura receives its vascular supply from the intercostal, internal thoracic, and musculophrenic arteries. Venous drainage is accomplished by way of the systemic veins in the adjacent parts of the chest wall. The bronchial vessels supply the visceral pleura. There exists no innervation to the visceral pleura and therefore no sensation.⁵ The phrenic nerve innervates the parietal pleura of the mediastinum and central diaphragm, whereas the intercostal nerves innervate the parietal pleura of the costal region and peripheral diaphragm.

Irritation of the intercostally innervated pleura may result in the referral of pain to the thoracic or abdominal walls, and irritation of the phrenic-supplied pleura can result in referred pain in the lower neck and shoulder.⁹

Several complications can affect pleural integrity. Infection with resultant inflammatory response within the pleura is termed pleuritis or pleurisy and is best appreciated through the presence of pleural chest pain and an abnormal pleural friction rub on auscultation.⁹ A pleural effusion refers to a buildup of fluid in the pleural space commonly seen after cardiothoracic surgery or with cancer. This is evidenced by diminished or absent breath sounds in the area of the effusion, is more likely to be in gravity-dependent areas, and is accompanied by reduced lung volumes. Blood in the pleural space is termed a hemothorax, whereas air in the pleural space from a collapsed lung is termed a pneumothorax. Finally, a bacterial infection with resultant pus in the pleural space is referred to as empyema.

Management for several of these complications of the pleural space is achieved through insertion of a chest tube into the pleural space to drain pleural secretions or to restore a negative pressure within the space and allow for lung inflation. A needle aspiration of fluid from the space, a thoracentesis, may be performed for patients with large pleural effusions.

Lungs

The lungs are located on either side of the thoracic cavity, separated by the mediastinum. Each lung lies freely within its corresponding pleural cavity, except where it is attached to the heart and trachea by the root and pulmonary ligament. The substance of the lung (the parenchyma) is normally porous and spongy in nature. The surfaces of the lungs are marked by numerous intersecting lines that indicate the polyhedral (secondary) lobules of the lung. The lungs are basically cone shaped and are described as having an apex, a base, three borders (anterior, inferior, and posterior), and three surfaces (costal, medial, and diaphragmatic).

The apex of each lung is situated in the root of the neck, its highest point being approximately 1 inch above the middle third of each clavicle. The base of each lung is concave, resting on the convex surface of the diaphragm. The inferior border of the lung separates the base of the lung from its costal surface; the posterior border separates the costal surface from the vertebral aspect of the mediastinal surface; the anterior border of each lung is thin and overlaps the front of the pericardium. In addition, the anterior border of the left lung presents a cardiac notch. The costal surface of each lung conforms to the shape of the

overlying chest wall. The medial surface of each lung may be divided into vertebral and mediastinal aspects. The vertebral aspect contacts the respective sides of the thoracic vertebrae and their intervertebral disks, the posterior intercostal vessels, and nerves. The mediastinal aspect is notable for the cardiac impression; this concavity is larger on the left than on the right lung to accommodate the projection of the apex of the heart toward the left. Just posterior to the cardiac impression is the hilus, where the structures forming the root of the lung enter and exit the parenchyma. The extension of the pleural covering below and behind the hilus from the root of the lung forms the pulmonary ligament.

Hila and roots

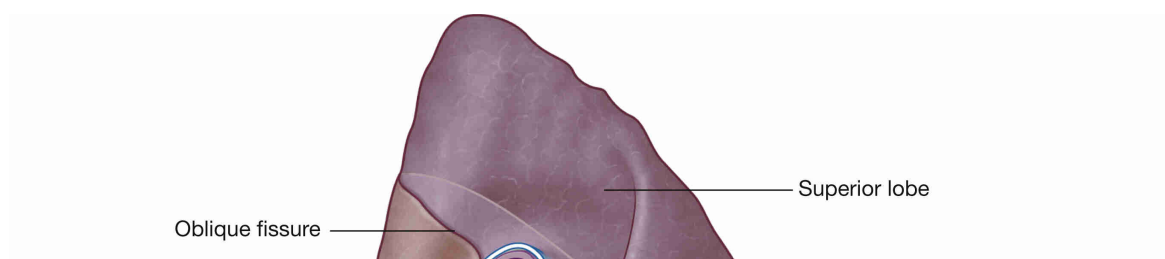
The point at which the nerves, vessels, and primary bronchi penetrate the parenchyma of each lung is called the hilus (Fig. 1.9A and B). The structures entering the hila of the lungs and forming the roots of each of the lungs are the principal bronchus, the pulmonary artery, the pulmonary veins, the bronchial arteries and veins, the pulmonary nerve plexus, and the lymph vessels. They lie next to the vertebral bodies of the fifth, sixth, and seventh thoracic vertebrae. The right root lies behind the superior vena cava and a portion of the right atrium, below the end of the azygos vein; the left root lies below the arch of the aorta and in front of the descending thoracic aorta. The pulmonary ligament lies below the root; the phrenic nerve and the anterior pulmonary plexus lie in front of the root; the vagus nerve and posterior pulmonary plexus lie behind the root.

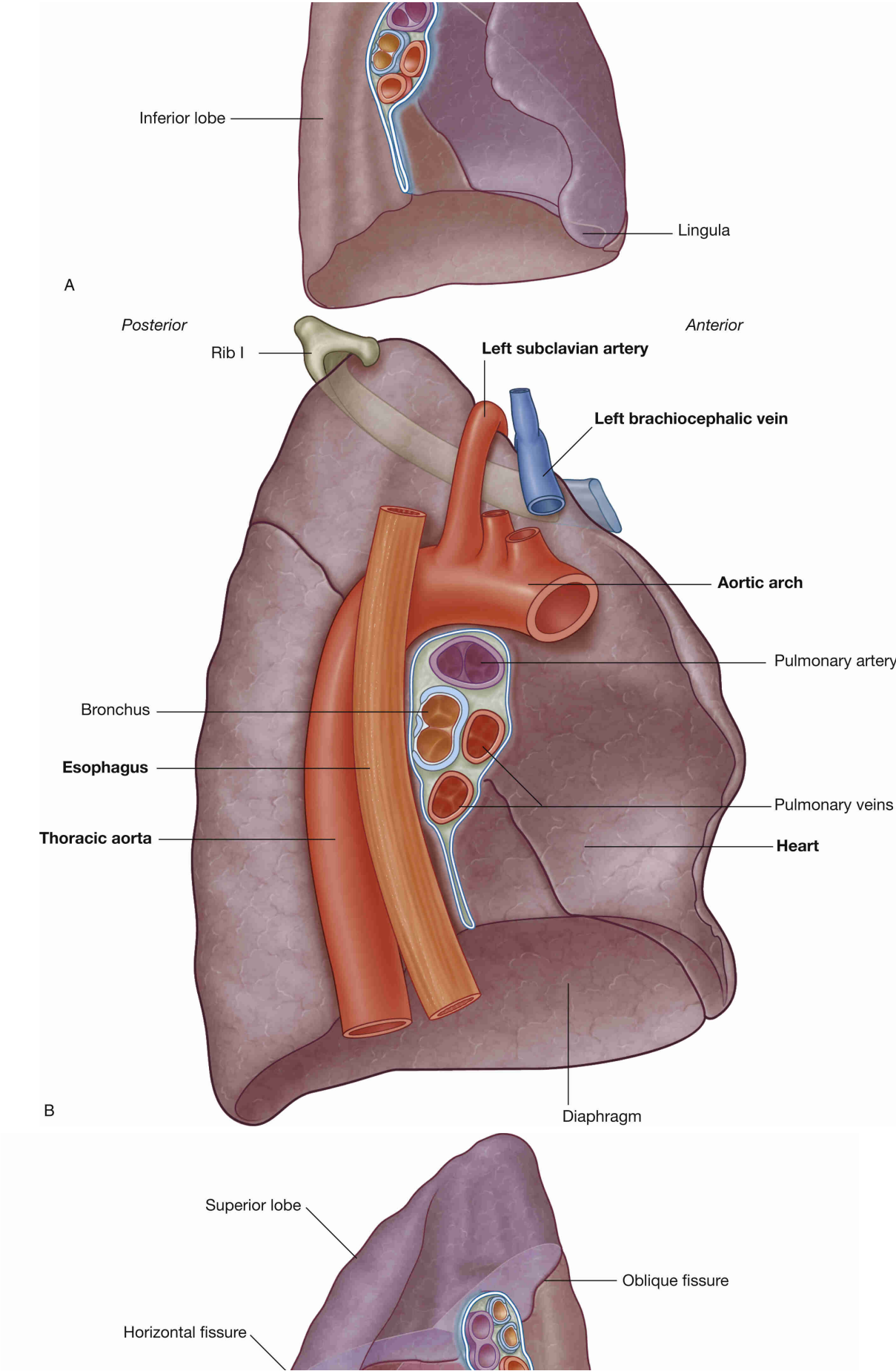
Lobes, fissures, and segments

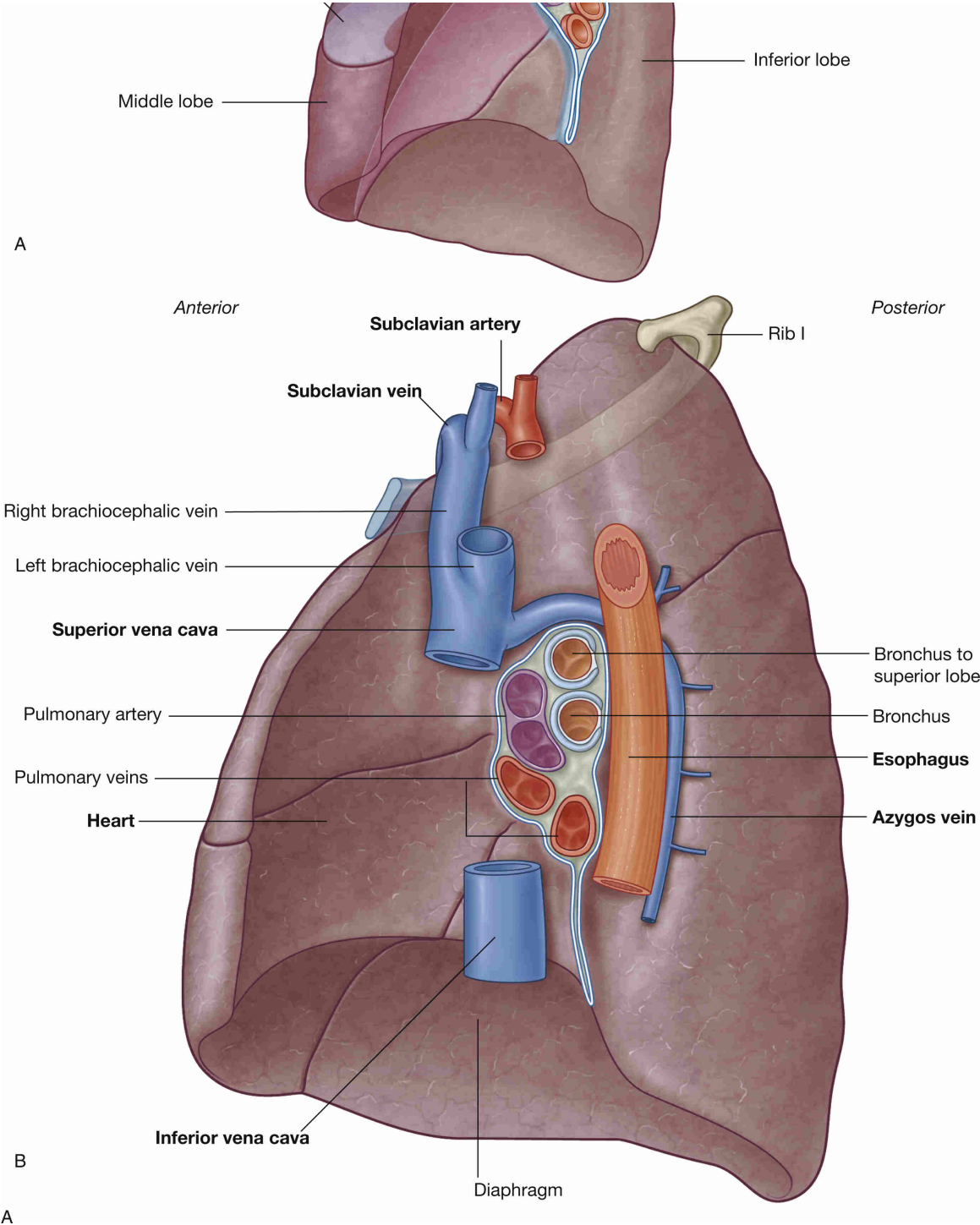
The right lung consists of three lobes, including the right upper lobe (RUL), right middle lobe (RML), and right lower lobe (RLL). Two fissures separate these three lobes from one another. The upper and middle lobes of the right lung are separated from the lower lobe by the oblique (major) fissure (Fig. 1.10). Starting on the medial surface of the right lung at the upper posterior aspect of the hilus, the oblique fissure runs upward and backward to the posterior border at about the level of the fourth thoracic vertebra; it then descends anteroinferiorly across the anterior costal surface to intersect the lower border of the lung approximately 5 inches from the median plane and then passes posterosuperiorly to rejoin the hilus just behind and beneath the upper pulmonary vein. The RML is separated from the RUL by the horizontal (minor) fissure that joins the oblique fissure at the midaxillary line at about the level of the fourth rib and runs horizontally across the costal surface of the lung to about the level of the fourth costal cartilage; on the medial surface, it passes backward to join the hilus near the upper-right pulmonary vein.

Each lobe of the right lung is further subdivided into segments. The RUL has three segments, including the apical, posterior, and anterior segments. This lobe extends to the level of the fourth rib anteriorly and is adjacent to ribs 3 to 5 posteriorly. The RML is subdivided into the lateral and medial lobes. This lobe is the smallest of the three lobes. Its inferior border is adjacent to the fifth rib laterally and the sixth rib medially. The lowermost lobe, the RLL, consists of four segments (anterior basal, superior basal, lateral basal, and posterior basal). The superior border of the RLL is at the level of the sixth thoracic vertebra and extends inferiorly down to the diaphragm. During maximal inspiration, the inferior border of the RLL may extend to the second lumbar vertebra and superimpose over the superior aspects of the kidney.

The left lung is relatively smaller than the right lung and has only two lobes, including the left upper lobe (LUL) and left lower lobe (LLL). The left lung is divided into upper and lower lobes by the oblique fissure, which is somewhat more vertically oriented than that of the right lung; there is no horizontal fissure. The portion of the left lung that corresponds to the right lung is termed the lingular segment and is a part of the LUL. Posteriorly, the inferior border of the LUL is at the level of the 6th rib, and the LLL is at the level of the 11th rib.







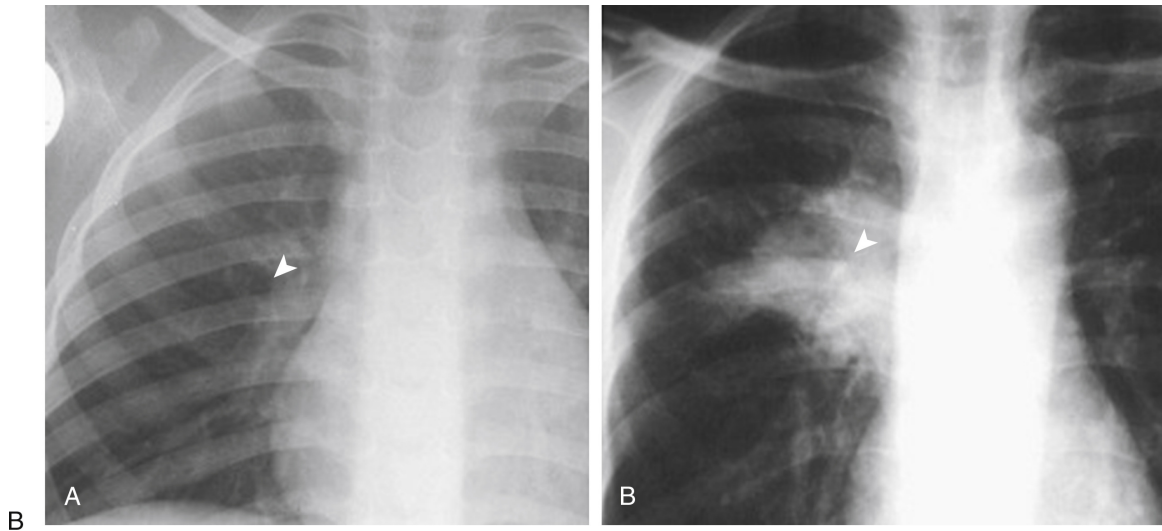


FIGURE 1.9 (A and B) Hilum area of lungs.

A, From Drake RL, Vogl AW, Mitchell A, *Gray's anatomy for students*, ed 4, Philadelphia, 2020, Elsevier; **B**, From Savvas A, Vanhoenacker FM, DeBacker AI. Advances in imaging chest tuberculosis: blurring of differences between children and adults, *Clin Chest Med* 30[4]:717–744, 2009.

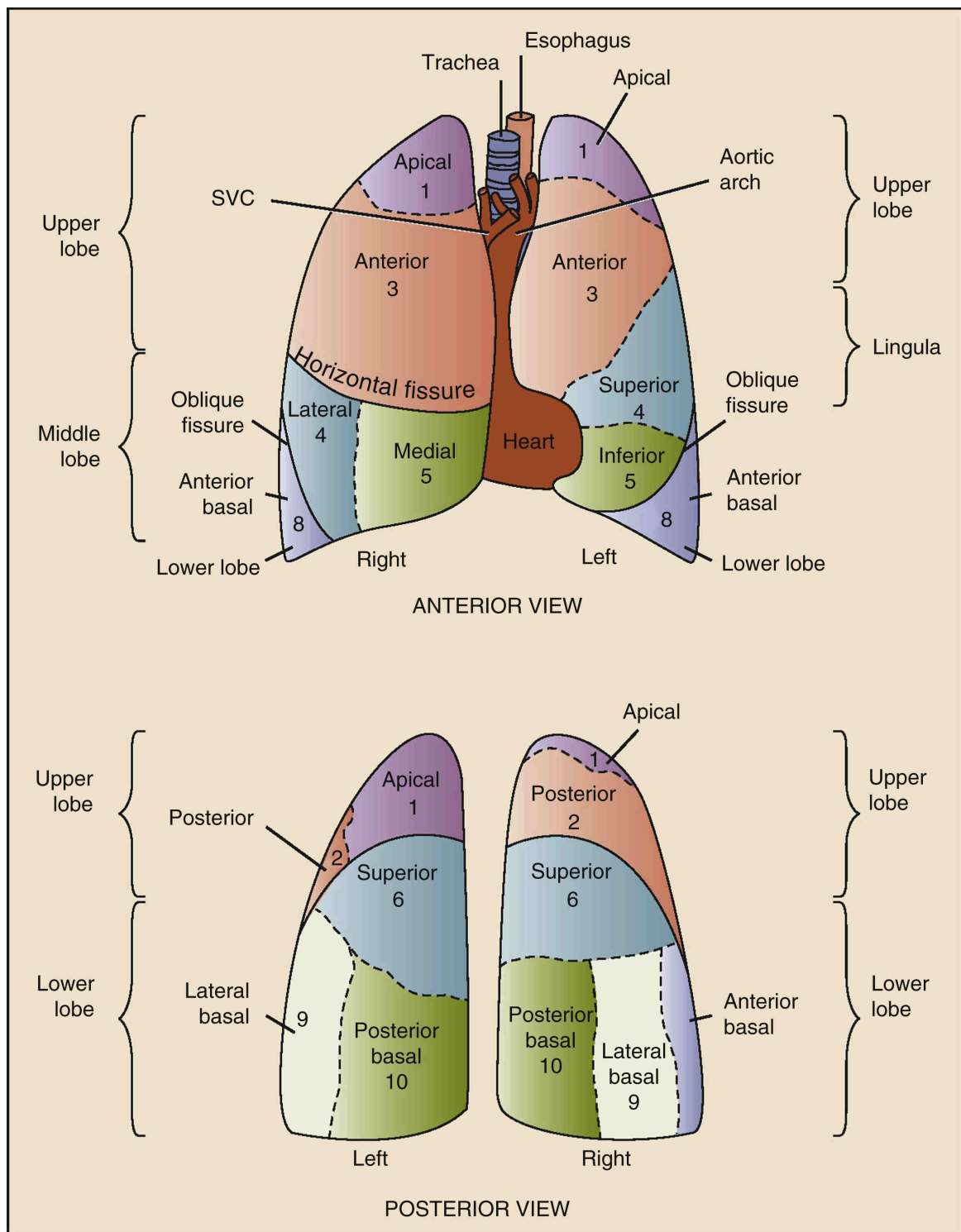


FIGURE 1.10 Topography of the lung demonstrating the lobes, segments, and fissures. The fissures (or chasms) demarcate the lobes in each lung. Numbers refer to specific bronchopulmonary segments. SVC, Superior vena cava.

From Koeppen B, Stanton B: *Berne and Levy physiology*, ed 6, Philadelphia, 2000, Mosby.

Table 1.1**Topographic Boundaries for the Bronchopulmonary Lung Segments**

Lobe	Segment	Borders
Upper lobe	Anterior segment (right or left)	Upper border: clavicle Lower border: a horizontal line at the level of the third intercostal space (ICS), or fourth rib, anteriorly
	Apical segment (R) or apical aspect, apicoposterior segment (L)	Anteroinferior border: clavicle Posteroinferior border: a horizontal line at the level of the upper lateral border of the spine of the scapula
	Posterior segment (R) or posterior aspect, apicoposterior segment (L)	Upper border: a horizontal line at the level of the upper lateral border of the spine of the scapula Lower border: a horizontal line at, or approximately 1 inch below, the inferomedial aspect of the spine of the scapula
Middle lobe (R) or lingula (L)		Upper border: a horizontal line at the level of the third ICS, or fourth rib, anteriorly Lower and lateral borders: the oblique fissure (a horizontal line at the level of the sixth rib anteriorly) extending to the anterior axillary line; from the anterior axillary line, angling upward to approximately the fourth rib at the posterior axillary line The midclavicular line separates the medial and lateral segments of the right middle lobe A horizontal line at the level of the fifth rib, anteriorly, separates the superior and inferior lingular segments
Lower lobe	Superior (basal) segment (right or left)	Upper border: a horizontal line at, or approximately 1 inch below, the inferomedial aspect of the spine of the scapula Lower border: a horizontal line at, or approximately 1 inch above, the inferior angle of the scapula
	Posterior (basal) segment (right or left)	Upper border: a horizontal line at, or approximately 1 inch above, the inferior angle of the scapula Lateral border: a "plumb line" bisecting the inferior angle of the scapula Lower border: a horizontal line at the level of the 10th ICS, posteriorly
	Lateral (basal) segment (right or left)	Upper border: a horizontal line at, or approximately 1 inch above, the inferior angle of the scapula Medial border: a "plumb line" bisecting the inferior angle of the scapula Lateral border: the midaxillary line Lower border: a horizontal line at the level of the 10th ICS, posteriorly

Lobe	Segment	Borders
	Anterior (basal) segment (R) or anterior aspect, anteromedial (basal) segment (L)	Upper border: the oblique fissure (a horizontal line at the level of the sixth rib anteriorly, extending to the anterior axillary line; from the anterior axillary line, angling upward to approximately the fifth rib at the midaxillary line) Lateral border: the midaxillary line

Table 1.1 describes the topographic boundaries for the bronchopulmonary segments of each lung. Fig. 1.11 shows the bronchopulmonary segments and Fig. 1.12 shows the bronchopulmonary segment anatomy.

Clinical tip

An understanding of the various lobes and segments and their anatomic orientation is essential for appropriate positioning and removal of secretions from various aspects of the lung during bronchopulmonary hygiene procedures.

Upper respiratory tract

Nose

The nose is a conglomerate of bone and hyaline cartilage. The nasal bones (right and left), the frontal processes of the maxillae, and the nasal part of the frontal bone combine to form the bony framework of the nose. The septal, lateral, and major and minor alar cartilages combine to form the cartilaginous framework of the nose. The periosteal and perichondral membranes blend to connect the bones and cartilages to one another.

Three major muscles assist with movement of the bony framework of the nose. The procerus muscle wrinkles the skin of the nose. The nasalis muscle has two parts, including the transverse and alar portions, and assists in flaring the anterior nasal aperture.⁸ Finally, the depressor septi muscle works with the nasalis muscle to flare the nostrils.⁸ Skin covers the external nose.

The nasal cavity is a wedge-shaped passageway divided vertically into right and left halves by the nasal septum and compartmentalized by the paranasal sinuses (Fig. 1.13). Opening anteriorly via the nares (nostrils) to the external environment, the nasal cavity blends posteriorly with the nasopharynx. The two halves are essentially identical, having a floor, medial and lateral walls, and a roof divided into three regions: the vestibule, the olfactory region, and the respiratory region.

The primary respiratory functions of the nasal cavity include air conduction, filtration, humidification, and temperature control; it also plays a role in the olfactory process. Three nasal conchae project into the nasal cavity from the lateral wall toward the medial wall; they are named the superior, middle, and inferior conchae. The conchae serve to increase the respiratory surface area of the nasal mucous membrane for greater contact with inspired air. The vestibule of the nasal cavity is lined with skin containing many coarse hairs and sebaceous and sweat glands. Mucous membrane lines the remainder of the nasal cavity. Fig. 1.14 depicts examples of some selected types of mucosal coverings in the upper and lower respiratory tracts.

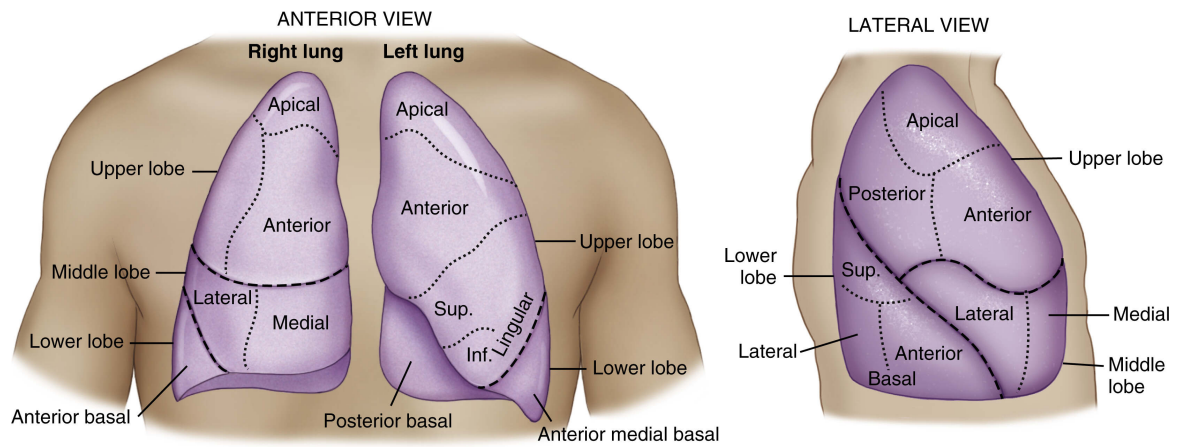
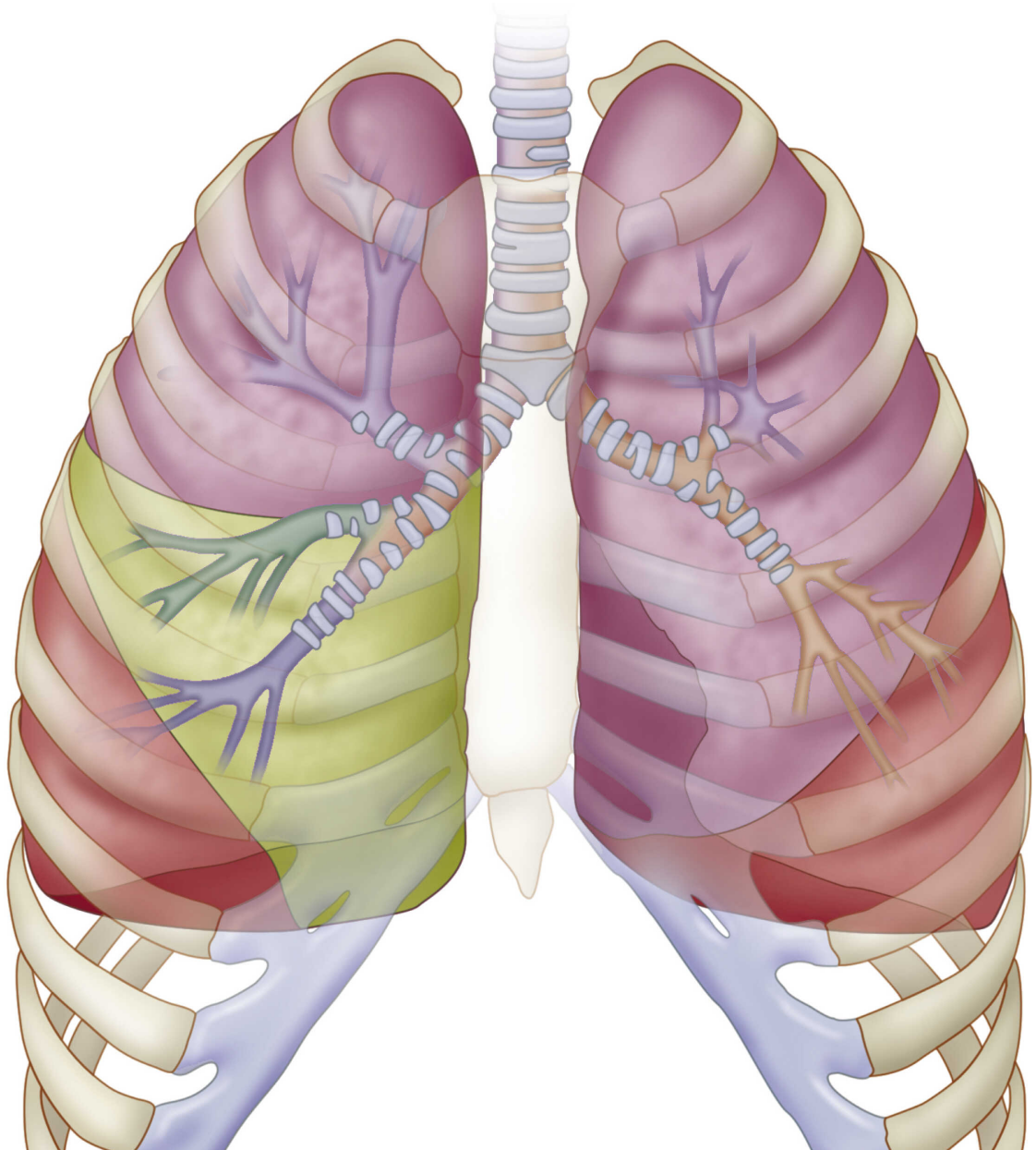


FIGURE 1.11 Anterior and lateral views of the bronchopulmonary segments as seen projected to the surface of the lungs.



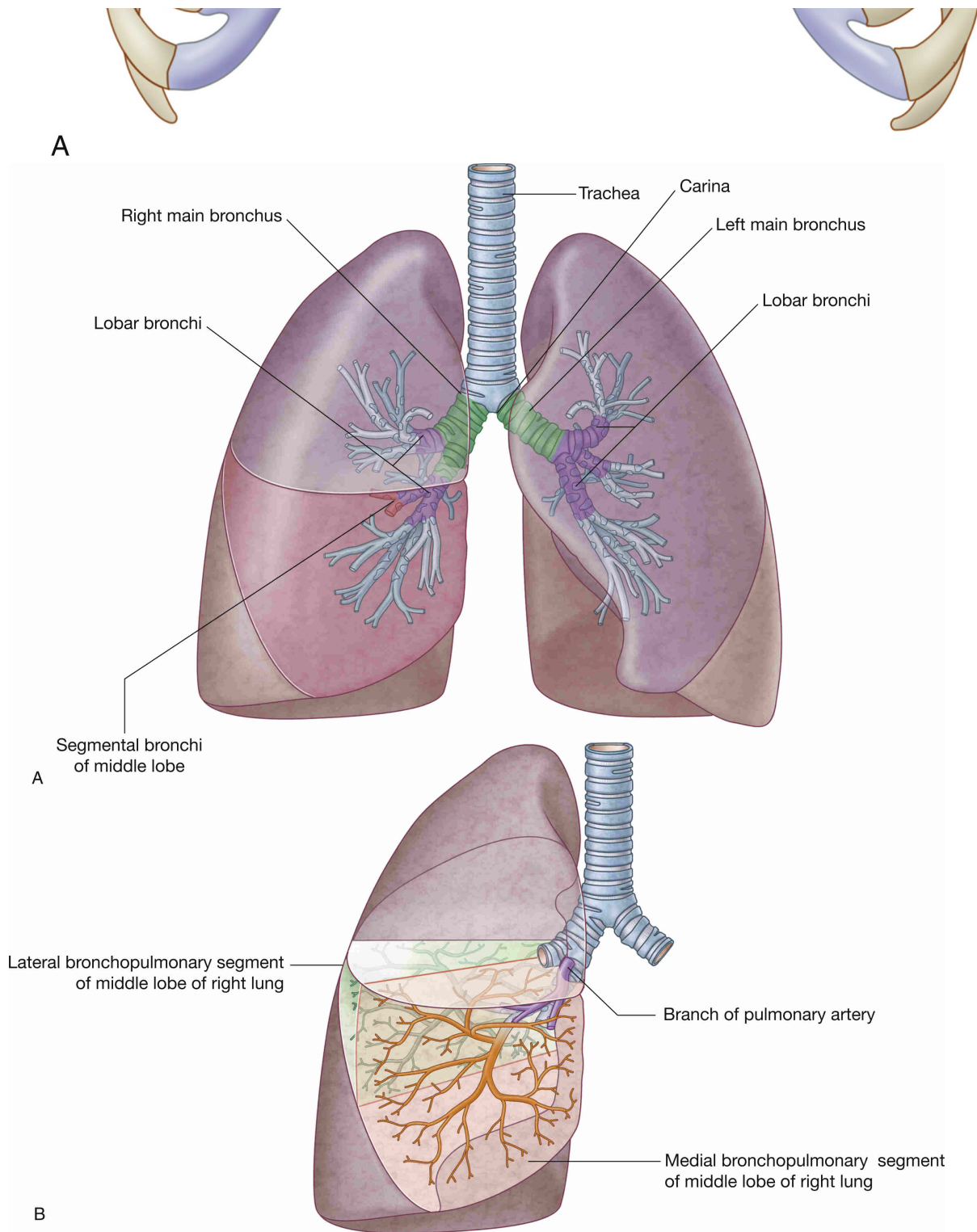


FIGURE 1.12 (A) Structure of the airways. (B) Bronchopulmonary segmental anatomy.

A, From Patton K, Thibodeau G, Douglas M: *Essentials of Anatomy and Physiology*, ed 1, St. Louis, 2011, Elsevier. (B), From Drake RL, Vogl AW, Mitchell A, *Gray's Anatomy for Students*, ed 4, Philadelphia, 2020, Elsevier.

The olfactory region of the nasal cavity is distinguished by specialized mucosa. This pseudostratified olfactory epithelium is composed of ciliated receptor cells, nonciliated sustentacular cells, and basal cells

that help to provide a sense of smell.⁸ Sniffing increases the volume of inspired air entering the olfactory region, allowing the individual to smell something specific.⁴

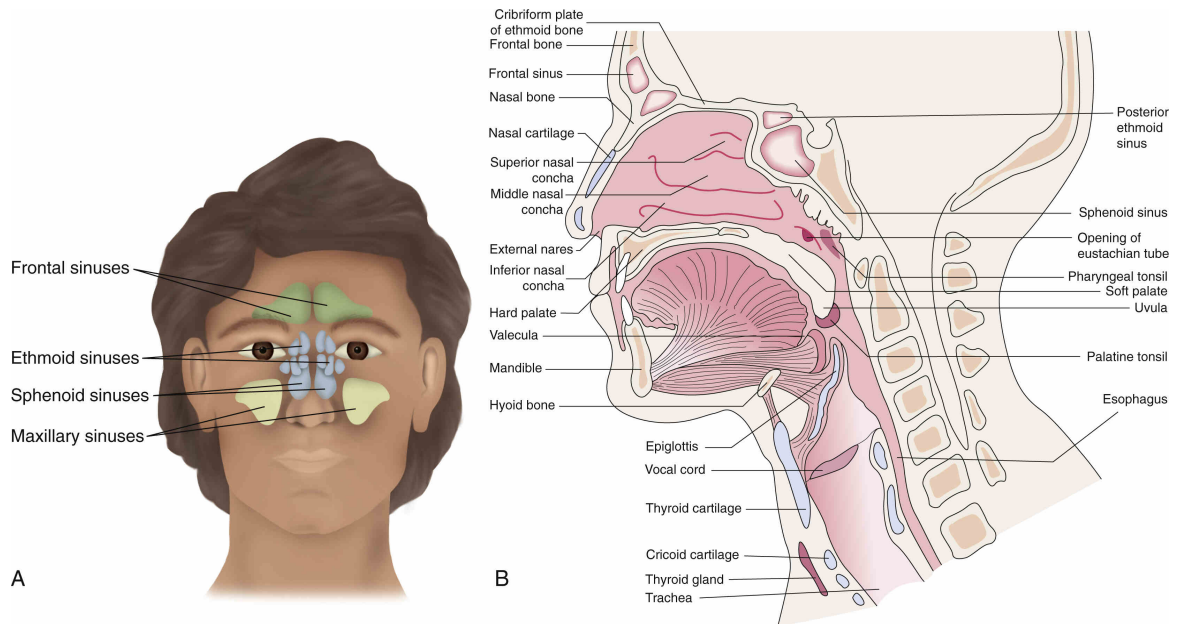
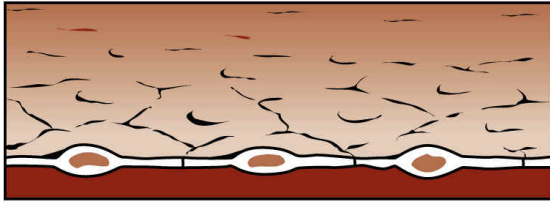


FIGURE 1.13 (A) Positions of the frontal, maxillary, sphenoid, and ethmoid sinuses; the nasal sinuses are named for the bones in which they occur. (B) Midsagittal section through the upper airway.

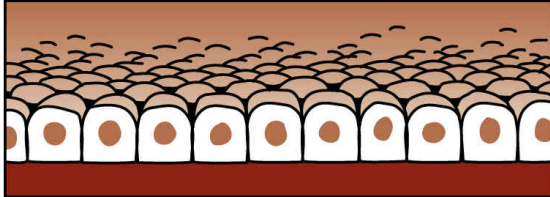
From Wilkins RE: *Fundamentals of respiratory care*, ed 9, St. Louis, 2009, Mosby.

SQUAMOUS

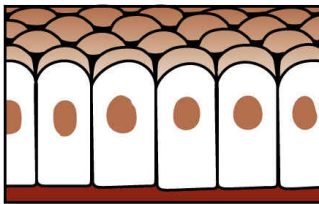


including mesothelium—lining coelomic surfaces; endothelium—lining vascular channels. Structural variants include continuous, discontinuous, and fenestrated endothelia.

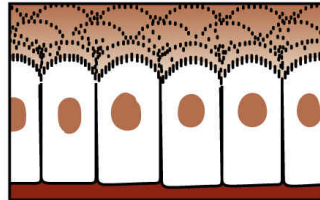
CUBOIDAL



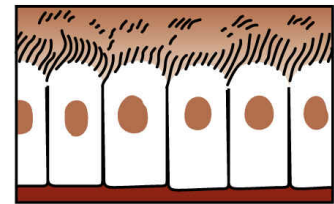
COLUMNAR



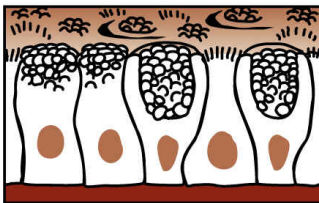
Without surface specialization



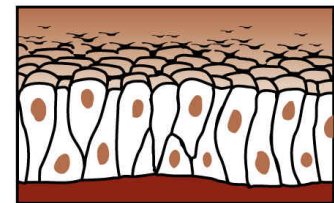
With microvilli (brush/striated border)



Ciliated

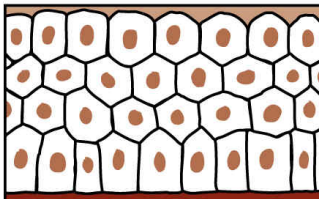


Glandular



Pseudostratified (distorted columnar)

STRATIFIED CUBOIDAL/COLUMNAR



TRANSITIONAL

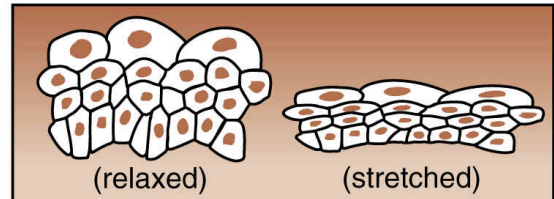


FIGURE 1.14 Types of cells composing the mucosal lining of the upper and lower respiratory tracts.

Modified from Williams PL, Warwick R, Dyson M, et al., editors: *Gray's anatomy*, ed 37, New York, 1989, Churchill Livingstone.

The respiratory region is lined with a mixture of columnar or pseudostratified ciliated epithelial cells, goblet cells, nonciliated columnar cells with microvilli, and basal cells. Serous and mucous glands, which open to the surface via branched ducts, underlie the basal lamina of the respiratory epithelium. ¹⁰ The submucosal glands and goblet cells secrete an abundant quantity of mucus over the mucosa of the nasal

cavity, making it moist and sticky. Turbulent airflow, created by the conchae, causes inhaled dust and other particulate matter larger than approximately 10 μm to “rain out” onto this sticky layer, which is then moved by ciliary action backward and downward out of the nasal cavity into the nasopharynx at an average rate of about 6 mm per minute. ^{11, 12}

Clinical tip

Nasotracheal suctioning must be performed with caution in individuals with low platelet counts because of the likelihood of trauma and bleeding to superficial nasal conchae and cells within the nasal cavity. The placement of a nasopharyngeal airway or nasal trumpet may reduce trauma with recurrent blind suctioning procedures in these patients.

Individuals with seasonal allergies who are prone to developing sinus infections are also prone to developing bronchitis if the infection leaves the sinus cavities and drops down the throat to the bronchioles.

Pharynx

The pharynx is a musculomembranous tube approximately 5 to 6 inches long and located posterior to the nasal cavity. It extends from the base of the skull to the esophagus that corresponds with a line extending from the sixth cervical vertebra to the lower border of the cricoid cartilage. The pharynx consists of three parts: the nasopharynx, the oropharynx, and the laryngopharynx.

Nasopharynx

The nasopharynx is a continuation of the nasal cavity, beginning at the posterior nasal apertures and continuing backward and downward. Its roof and posterior wall are continuous; its lateral walls are formed by the openings of the eustachian tubes; and its floor is formed by the soft palate anteriorly and the pharyngeal isthmus (the space between the free edge of the soft palate and the posterior wall of the pharynx), which marks the transition to the oropharynx. The epithelium of the nasopharynx is composed of ciliated columnar cells.

Oropharynx

The oropharynx extends from the soft palate and pharyngeal isthmus superiorly to the upper border of the epiglottis inferiorly. Anteriorly, it is bounded by the oropharyngeal isthmus (which opens into the mouth) and the pharyngeal part of the tongue. The posterior aspect of the oropharynx is at the level of the body of the second cervical vertebra and upper portion of the body of the third cervical vertebra. The epithelium in the oropharynx is composed of stratified squamous cells.

Laryngopharynx

The laryngopharynx extends from the upper border of the epiglottis to the inferior border of the cricoid cartilage and the esophagus. The laryngeal orifice and the posterior surfaces of the arytenoid and cricoid cartilages form the anterior aspect of the laryngopharynx. The posterior aspect is at the level of the lower portion of the third cervical vertebra, the bodies of the fourth and fifth cervical vertebrae, and the upper portion of the body of the sixth cervical vertebra. The epithelium in the laryngopharynx is composed of stratified squamous cells.

Larynx

The larynx, or voice box, is a complex structure made up of several cartilages and forms a connection between the pharynx and the trachea. The position of the larynx depends on the age and sex of the individual, being opposite the third to sixth cervical vertebrae in the adult male and somewhat higher in adult females and children.

The larynx consists of the endolarynx and its surrounding cartilaginous structures. The endolarynx is made of two sets of folds, including the false vocal cords (supraglottis) and true vocal cords. ⁸ Between the true cords are slit-shaped spaces that form the glottis. A space exists above the false vocal cords and is termed the vestibule. Six supporting cartilages, including three large (epiglottis, thyroid, cricoid) and three smaller (arytenoid, corniculate, cuneiform), prevent food, liquids, and foreign objects from entering the airway. Two sets of laryngeal muscles (internal and external) play important roles in swallowing, ventilation, and vocalization. The larynx controls airflow and closes to increase intrathoracic pressure to

generate an effective cough. Sounds with speech are created as expired air vibrates over the contracting vocal cords.

Clinical tip

Endotracheal intubation may cause damage to structures within the larynx, producing an inflammatory response—laryngitis—where patients present with hoarseness and pain during speech.

Lower respiratory tract

The lower respiratory tract extends from the level of the true vocal cords in the larynx to the alveoli within the lungs. In general, the lower respiratory tract may be divided into two parts: the tracheobronchial tree, or conducting airways, and the acinar or terminal respiratory units.

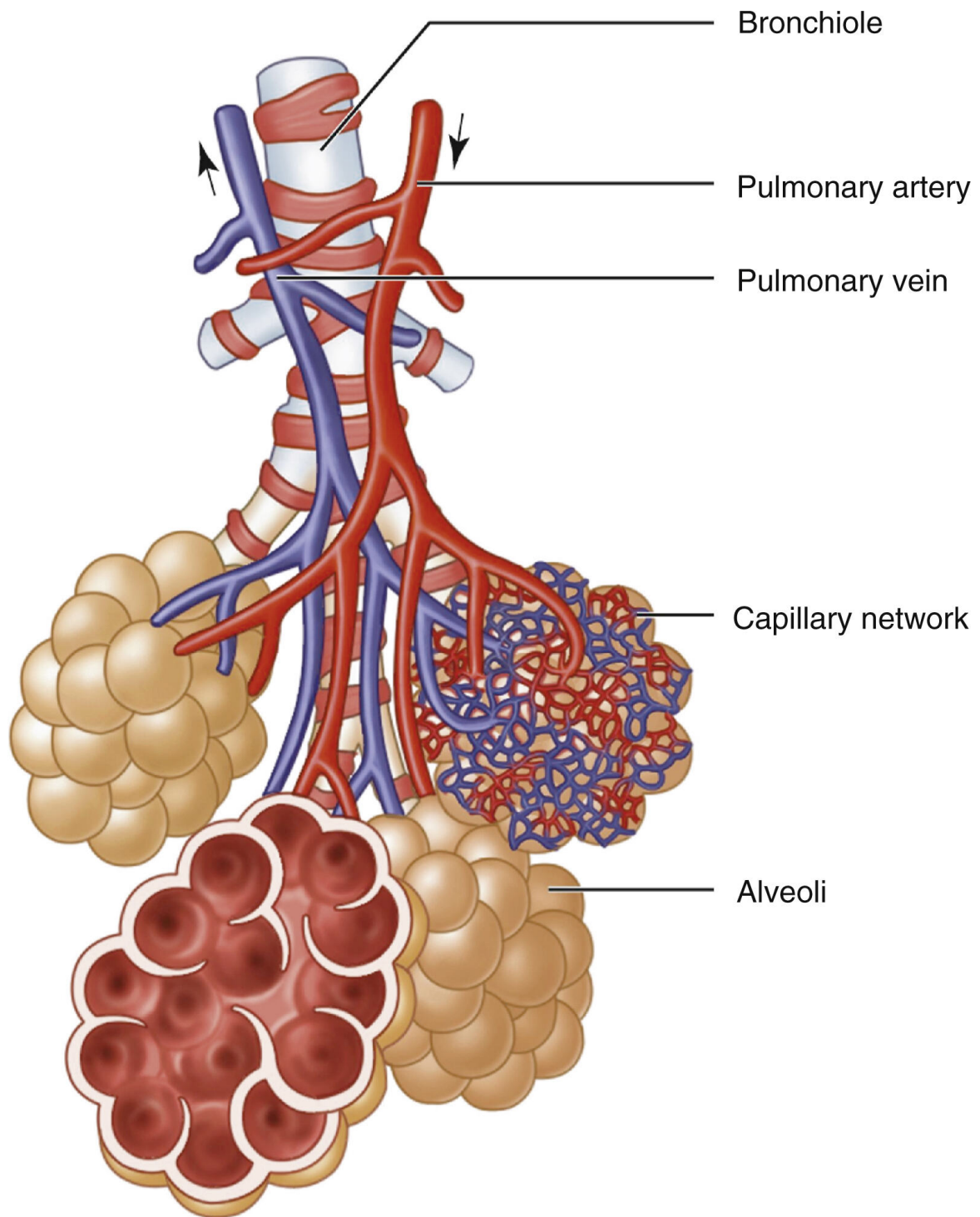


FIGURE 1.15 A view of the terminal respiratory unit showing the alveolar sac and blood supply surrounding.

From Malamed SF: *Sedation*, ed 4, St. Louis, 2010, Mosby.

Tracheobronchial tree or conducting airways

The conducting airways are not directly involved in the exchange of gases in the lungs. They simply conduct air to and from the respiratory units. Airway diameter progressively decreases with each succeeding generation of branching, starting at approximately 1 inch in diameter at the trachea and reaching 1 mm or less at the terminal bronchioles. The cartilaginous rings of the larger airways give way to irregular cartilaginous plates, which become smaller and more widely spaced with each generation of

branching, until they disappear at the bronchiolar level.¹³ There may be as many as 16 generations of branching in the conducting airways from the mainstem bronchi to the terminal bronchioles (Fig. 1.15).¹⁴

Trachea

The trachea is a tube approximately 4 to 4.5 inches long and approximately 1 inch in diameter, extending downward along the midline of the neck, ventral to the esophagus. As it enters the thorax, it passes behind the left brachiocephalic vein and artery and the arch of the aorta. At its distal end, the trachea deviates slightly to the right of midline before bifurcating into right and left mainstem bronchi. Between 16 and 20 incomplete rings of two or more hyaline cartilages are often joined together along the anterior two-thirds of the tracheal circumference, forming a framework for the trachea. Fibrous and elastic tissues and smooth muscle fibers complete the ring posteriorly. The first and last tracheal cartilages differ somewhat from the others: the first is broader and is attached by the cricotracheal ligament to the lower border of the cricoid cartilage of the larynx. The last is thicker and broader at its middle, where it projects a hook-shaped process downward and backward from its lower border—the carina—between the two mainstem bronchi. The carina is located at the fifth thoracic vertebra or sternal notch and represents the cartilaginous wedge at the bifurcation of the trachea into the right and left mainstem bronchi.

Clinical tip

During suctioning procedures, the catheter is inserted to the level of the carina. When the catheter is in contact with the carina, a cough ensues along with a strong parasympathetic response. Therapists must monitor for adverse responses in heart rate and provide supplemental oxygen as needed.

Mainstem and lobar bronchi

The right mainstem bronchus is wider and shorter than its left counterpart, and it diverges at approximately a 25-degree angle from the trachea. It passes laterally downward behind the superior vena cava for approximately 1 inch before giving off its first branch—the upper lobe bronchus—and entering the root of the right lung. Approximately 1 inch farther, it gives off its second branch—the middle lobe bronchus—from within the oblique fissure. Thereafter, the remnant of the mainstem bronchus continues as the lower lobe bronchus.

The left mainstem bronchus leaves the trachea at an angle of approximately 40 to 60 degrees and passes below the arch of the aorta and behind the left pulmonary artery, proceeding for a little more than 2 inches before it enters the root of the left lung, giving off the upper lobe bronchus and continuing on as the lower lobe bronchus. The left lung has no middle lobe, which is a major distinguishing feature in the general architecture of the lungs.

Clinical tip

The angulation of the right mainstem bronchus relative to the position of the trachea predisposes foreign objects, food, and fluids to enter the right lung. Consequently, aspiration is relatively more common in the right lung compared with the left lung.

Segmental and subsegmental bronchi

Each of the lobar bronchi gives off two or more segmental bronchi; an understanding of their anatomy is essential to the appropriate assessment and treatment of pulmonary disorders (see Fig. 1.12). The RUL bronchus divides into three segmental bronchi about a half inch from its own origin: the first—the apical segmental bronchus—passes superolaterally toward its distribution in the apex of the lung; the second—the posterior segmental bronchus—proceeds slightly upward and posterolaterally to its distribution in the posteroinferior aspect of the upper lobe; the third—the anterior segmental bronchus—runs anteroinferiorly to its distribution in the remainder of the upper lobe. The RML bronchus divides into a lateral segmental bronchus, which is distributed to the lateral aspect of the middle lobe, and a medial segmental bronchus to the medial aspect. The RLL bronchus first gives off a branch from its posterior surface—the superior segmental bronchus—which passes posterosuperiorly to its distribution in the upper portion of the lower lobe. Then, after continuing to descend posterolaterally, the lower lobe bronchus yields the medial basal segmental bronchus (distributed to a small area below the hilus) from its anteromedial surface. The next

offshoots from the lower lobe bronchus are the anterior basal segmental bronchus, which continues its descent anteriorly, and a very small trunk that almost immediately splits into the lateral basal segmental bronchus (distributed to the lower lateral area of the lower lobe) and the posterior basal segmental bronchus (distributed to the lower posterior area of the lower lobe).

The LUL bronchus extends laterally from the anterolateral aspect of the left mainstem bronchus before dividing into correlates of the right upper and middle lobar bronchi. However, these two branches remain within the LUL because there is no left middle lobe. The uppermost branch ascends for approximately one-third of an inch before yielding the anterior segmental bronchus, and then continues its upward path as the apicoposterior segmental bronchus before subdividing further into its subsegmental distribution. The caudal branch descends anterolaterally to its distribution in the anteroinferior area of the LUL, a region called the lingula. This lingular bronchus divides into the superior lingular and inferior lingular segmental bronchi.

The LLL bronchus descends posterolaterally for approximately one-third of an inch before giving off the superior segmental bronchus from its posterior surface (its distribution is similar to that of the RLL superior segmental bronchus). After another one-half to two-thirds of an inch, the lower lobe bronchus splits in two: the anteromedial division is called the anteromedial basal segmental bronchus, and the posterolateral division immediately branches into the lateral basal and posterior basal segmental bronchi. The distributions of these segmental bronchi are similar to those of their right-lung counterparts.

The epithelium of the upper regions of the conducting airways is pseudostratified and, for the most part, ciliated. The epithelium of the terminal and respiratory bronchioles is single layered and more cuboidal in shape, and many of the cells are nonciliated. The lamina propria, to which the epithelial basal lamina is attached, contains longitudinal bands of elastin throughout the length of the tracheobronchial tree that spread into the elastin network of the terminal respiratory units. The framework thus created is responsible for much of the elastic recoil of the lungs during expiration.

The most abundant types of cells in the bronchial epithelium are the ciliated cells. Ciliated cells are found in all levels of the tracheobronchial tree down to the level of the respiratory bronchioles. The cilia projecting from their luminal surfaces are intimately involved in the removal of inhaled particulate matter from the airways via the “mucociliary escalator” mechanism.

Two of the bronchial epithelial cells are mucus secreting: the mucous cells and serous cells.¹⁵ Mucous cells, formerly called goblet cells, are normally more numerous in the trachea and large airways, becoming less numerous with distal progression, until they are infrequently found in the bronchioles. Serous cells are much less numerous than mucous cells and are confined predominantly to the extrapulmonary bronchi. Both types of cells are nonciliated, although both exhibit filamentous surface projections.

Clinical tip

Smoking paralyzes ciliated epithelial cells. These cilia will be paralyzed for 1 to 3 hours after smoking a cigarette, or will be permanently paralyzed in chronic smokers.¹⁶ The inability of the mucociliary escalator to work increases the individual's risk for developing respiratory infections.

Terminal respiratory (acinar) units

The conducting airways terminate in gas-exchange airways made up of respiratory bronchioles, alveolar ducts, and alveoli (see [Fig. 1.13](#)). These structures together are termed the *acinus* and participate in gas exchange. The functional unit of the lung is the alveoli, where gas exchange occurs. The acinus is connected to the interstitium through a dense network of fibers. Two major types of epithelial cells exist along the alveolar wall. Squamous pneumocytes (type I) cells are flat and thin and cover approximately 93% of the alveolar surface. Granular pneumocytes (type II) cells are thick, are cuboidal shaped, cover 7% of the alveolar wall, and are involved in the production of surfactant.¹³ Surfactant is a lipoprotein that lowers alveolar surface tension at end expiration and thereby prevents the lung from collapsing. The alveoli, like the bronchi, contain cellular components of inflammation and immunity. The alveolar macrophage engulfs and ingests foreign material in the alveoli and provides a protective function against disease.

Capillaries composed of a single layer of endothelial cells deliver blood in close proximity to the alveoli. Capillaries can distend and accommodate to the volume of blood being delivered to the lung. The alveolar

capillary interface is where exchange of gases occurs. The thickness of the alveolar capillary membrane is between 0.5 and 1.0 μm .

Innervation of the lungs

The lungs are invested with a rich supply of afferent and efferent nerve fibers and specialized receptors. Parasympathetic fibers are supplied by preganglionic fibers from the vagal nuclei via the vagus nerves to ganglia around the bronchi and blood vessels. Postganglionic fibers innervate the bronchial and vascular smooth muscle, as well as the mucous cells and submucosal bronchial glands. The parasympathetic postganglionic fibers from thoracic sympathetic ganglia innervate essentially the same structures. Posterior and anterior pulmonary plexuses are formed by contributions from the postganglionic sympathetic and parasympathetic fibers at the roots of the lungs. In general, stimulation of the vagus nerve results in bronchial constriction, dilation of pulmonary arterial smooth muscle, and increased glandular secretion.¹⁷ Stimulation of the sympathetic nerves causes bronchial relaxation, constriction of pulmonary arterial smooth muscle, and decreased glandular secretion.¹⁷

Bronchodilators enhance sympathetic stimulation to the lungs to cause relaxation of bronchial smooth muscle cells and reduce secretions.

The cardiovascular system

Mediastinum

The mediastinum lies between the right and left pleura of the lungs and near the median sagittal plane of the chest. From an anteroposterior perspective, it extends from the sternum in front to the vertebral column behind and contains all the thoracic viscera except the lungs.⁸ It is surrounded by the chest wall anteriorly, the lungs laterally, and the spine posteriorly. It is continuous with the loose connective tissue of the neck and extends inferiorly onto the diaphragm. It is the central compartment of the thoracic cavity and contains the heart, the great vessels of the heart, esophagus, trachea, phrenic nerve, cardiac nerve, thoracic duct, thymus, and lymph nodes of the central chest.^{8, 13}

A shifting of the structures within the mediastinum (mediastinal shift) is appropriate to consider and examine on the chest radiograph in patients who have air trapped in the pleural space (pneumothorax) or after removal of a lung (pneumonectomy).³ In a tension pneumothorax or pneumonectomy, the mediastinum shift away from the affected or operated side.

Heart

The heart is the primary pump that circulates blood through the entire vascular system. It is closely related to the size of the body and is roughly the size of the individual's closed fist. It lies obliquely (diagonally) in the mediastinum, with two-thirds lying left of the midsagittal plane. The superior portion of the heart formed by the two atria is termed the base of the heart. It is broad and exists at the level of the second intercostal space in adults. The apex of the heart, defined by the tip of the left ventricle, projects into the fifth intercostal space at the midclavicular line.

The heart moves freely and changes its position during its contraction and relaxation phase, as well as during breathing. As the heart contracts, it moves anteriorly and collides with the chest wall. The portion of the heart that strikes the chest wall is the apex of the heart and is termed the point of maximum impulse.¹ Normally, this point is evidenced at the anatomic landmark of the apex, which is the fifth intercostal space at the midclavicular line. In terms of ventilation, quiet resting breathing does not alter the point of maximum impulse because of minimal excursion of the diaphragm. However, with deep inspiration, there is more significant inferior depression of the diaphragm, causing the heart to descend and rotate to the right, displacing the point of maximum impulse away from the normal palpable position.¹

Clinical tip

The point of maximum impulse is relatively more lateral in patients with left ventricular hypertrophy caused by an increase in left ventricular mass. Also patients with a pneumothorax and

resultant mediastinal shift will demonstrate an altered point of maximum impulse away from the normal anatomic position of the apex of the heart.

Tissue layers

Pericardium

The heart wall is made up of three tissue layers (Fig. 1.16). The outermost layer of the heart is a double-walled sac termed the pericardium, anchored to the diaphragm inferiorly and the connective tissue of the great vessels superiorly. The two layers of the pericardium include an outer parietal pericardium and an inner visceral pericardium, also referred to as the epicardium.⁸ The parietal pericardium is a tough, fibrous layer of dense, irregular connective tissue, whereas the visceral pericardium is a thin, smooth, and moist serous layer. Between the two layers of the pericardium is a closed space termed the pericardial space or pericardial cavity filled with approximately 10 to 20 mL of clear pericardial fluid.¹³ This fluid separates the two layers and minimizes friction during cardiac contraction.

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