2

Cardiovascular and Pulmonary Function in Health

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CHAPTER OUTLINE

KEY TERMS

Cardiopulmonary physiology
Functional anatomy
Control of breathing
Oxygen transport
Oxygen Transport pathway
Mechanics of breathing

Introduction

One of the key aims of the cardiopulmonary system is to deliver oxygen to the entire body. **Oxygen transport** is essential to life, activity, and participation in life consistent with the International Classification of Functioning, Disability and Health (ICF).[1] Maximizing the efficiency of the **oxygen transport pathway** promotes optimal mobility and independence, the cornerstones of quality of life and well-being. Attention to oxygen transport, including its deficits and threats to it, is the concern of physical therapists, irrespective of the primary clinical area of their practices. This is particularly true given the trend toward physical therapists' direct access to patients and the prevalence of lifestyle-related conditions, all of which affect oxygen transport either directly or indirectly.

Cardiovascular and pulmonary physical therapy consists of noninvasive interventions that can reverse or mitigate insults to oxygen transport. It can eliminate, delay, or reduce the need for medical interventions such as supplemental oxygen, intubation, mechanical ventilation, suctioning, bronchoscopy, chest tubes, surgery, and medications. To achieve these outcomes, the physical therapist must fully assess oxygen transport and prescribe optimal treatment interventions. This is possible only with a comprehensive understanding of the **functional anatomy** and underlying physiology so that the factors that determine and influence oxygen transport can be fully understood and assessed.

This chapter details these underlying mechanisms, which provides a conceptual basis for cardiovascular and pulmonary physical therapy practice.[2-13] Oxygen transport is the basis of life. Treatment of impaired or threatened oxygen transport (i.e., cardiovascular and pulmonary dysfunction) is a physical therapy priority.

In a healthy person, the oxygen transport system is perturbed by movement and activity, changes in body position, and emotional state. In a person with pathology, disruption of or threat to this system is a medical priority because of the threat to life or the impairment of functional capacity.

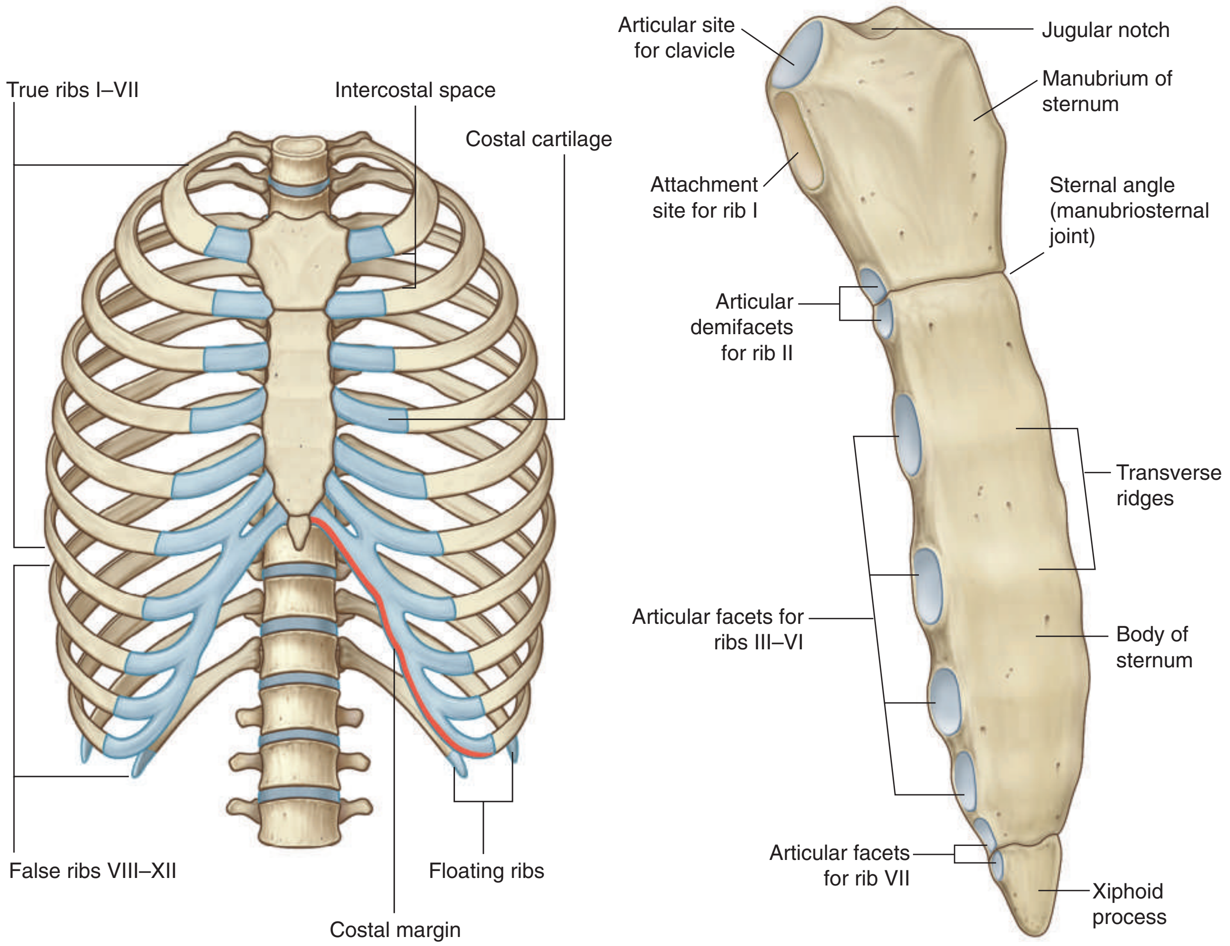
Functional Anatomy of the Thoracic Walls and Boundaries

The bony thorax covers and protects the principal organs of respiration and circulation in addition to the liver and the stomach (Fig. 2.1). The anterior surface is formed by the sternum and the costal cartilage. The lateral surfaces are formed by the ribs. The posterior surface is formed by the 12 thoracic vertebrae and the posterior part of the 12 ribs. At birth, the thorax is nearly circular, but during childhood and adolescence, it becomes more elliptical. In adulthood, the transverse diameter of the chest wall is greater than the anteroposterior diameter.

Bones

Sternum

The sternum, or breastbone, is a flat bone with three parts: manubrium, body, and xiphoid process. The manubrium is the widest and thickest bone of the sternum (see Fig. 2.1). Its upper border is scalloped by a central jugular notch, which can be palpated, and by two clavicular notches that articulate with the clavicles. The sternal angle is where the manubrium articulates with the sternum



• Fig. 2.1 Overview of the bony thorax. (From *Gray's Anatomy for Students*, 4th ed., 2020: figure 3.20; figure 3.23.)

at a slight angle; this is a landmark for the thoracic vertebrae T4 and T5, the second costal cartilages. The manubrium and body are joined by fibrocartilage, which may ossify in later life.

The body of the sternum is twice as long as the manubrium. It is a relatively thin bone and can be easily pierced by needles for bone marrow aspirations. The heart is located beneath and to the left of the lower third of the body of the sternum. Although it is attached by cartilage to the ribs, this portion of the sternum is flexible and can be depressed without breaking. This maneuver is used with care in closed cardiac massage to artificially circulate blood to the brain and extremities. The lower margin of the body is attached to the xiphoid process by fibrocartilage. This bone is the smallest of the three parts of the sternum and usually fuses with the body of the sternum in later life

Ribs

A large portion of the bony thoracic cage is formed by 12 ribs located on either side of the sternum (see Fig. 2.1). The first seven ribs connect posteriorly with the vertebral column and anteriorly through costal cartilages with the sternum. These are known as the *true ribs*. The remaining five ribs are known as the *false ribs*. The first three have their cartilage attached to the cartilage of the rib above. The last two are free or floating ribs. The ribs increase in length from the first to the seventh rib and then decrease to the twelfth rib. They also increase in obliquity until the ninth rib and then decrease in obliquity to the twelfth rib.

Each rib has a small head and a short neck that articulate with two thoracic vertebrae. The shaft of the rib curves gently from the neck to a sudden sharp bend: the angle of the rib. Fractures often occur at this site. A costal groove is located on the lower border of the shaft of the ribs. This groove houses the intercostal nerves and vessels (Fig. 2.2A and B). Chest tubes and needles are inserted above the ribs to avoid these vessels and nerves. The ribs are separated from each other by the intercostal spaces that contain the intercostal muscles.

Muscles of Respiration

Inspiration

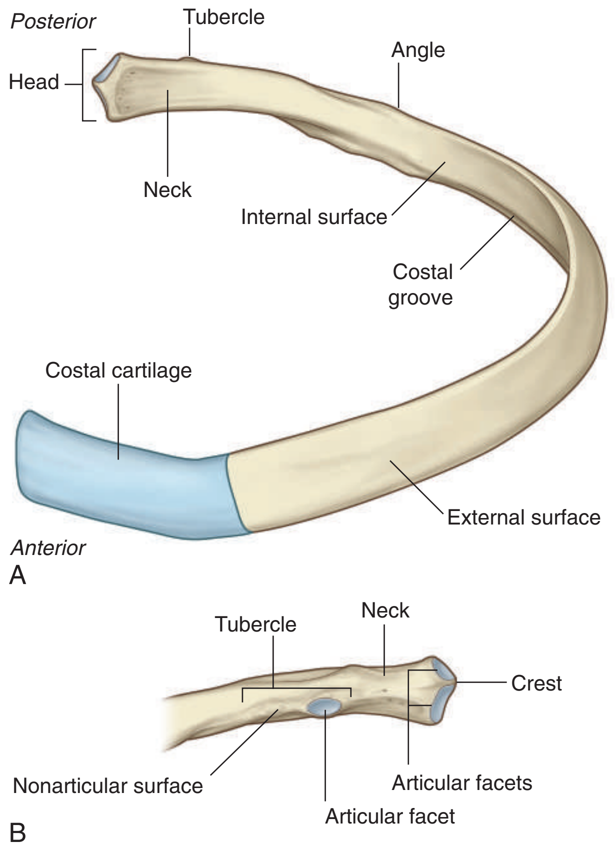
Inspiration is an active movement involving the contraction of the diaphragm and intercostal muscles. Some additional muscles are involved in labored or heavy breathing, which may be found during exertion or in disease. The accessory muscles include the sternocleidomastoid (SCM), scalene, serratus anterior, pectoralis major and minor, trapezius, and erector spinae muscles. The degree to which these accessory muscles are recruited depends on the severity of cardiovascular and pulmonary distress.

Diaphragm

The diaphragm is the principal muscle of respiration. It is a large, dome-shaped muscle that separates the thoracic and abdominal cavities. Its upper surface supports the pericardium (with which it is partially blended), heart, pleurae, and lungs. Its lower surface is almost completely covered by the peritoneum and overlies the liver, kidneys, suprarenal glands, stomach, and spleen (Fig. 2.3). This large muscle can be divided into right and left halves. Each half is made up of three parts: sternal, lumbar, and costal. These three parts insert into the central tendon, which lies just below the heart. The sternal part arises from the back of the xiphoid process and descends to the central tendon. On each side is a small gap, the sternocostal triangle, which is located between the sternal and costal parts. It transmits the superior epigastric vessels and is often the site of diaphragmatic hernias. The costal parts form the right and left domes. They arise from the inner surfaces of the lower four ribs and the lower six costal cartilages, then interdigitate and transverse the abdomen to insert into the anterolateral part of the central tendon, the central part of the diaphragm. The lumbar part arises from the bodies of the upper lumbar vertebrae and extends upward to the central tendon. The central tendon is a thin, strong aponeurosis situated near the center of the muscle, somewhat closer to the front of the body. It resembles a trefoil leaf, with its three divisions or leaflets. The right leaflet is the largest, the middle is the next largest, and the left leaflet is the smallest.

Major vessels traverse the diaphragm through one of three openings (see Fig. 2.3). The vena cava opening is located to the right of the midline in the central tendon and contains branches of the right phrenic nerve and the inferior vena cava. The esophageal opening is located to the left of the midline and contains the esophagus, vagal nerve trunks, and branches of the gastric vessels. The aortic opening is located in the midline and contains the aorta, the thoracic duct, and sometimes the azygos vein. The diaphragm is also pierced by branches of the left phrenic nerve, small veins, and lymph vessels.

The position of the diaphragm and its range of movement vary with posture, the degree of distention of the stomach, size of the intestines, size of the liver, and obesity. Average movement of the diaphragm in quiet respiration is 12.5 mm on the right and 12 mm on the left. This can increase to a maximum of 30 mm on the right and 28 mm on the left during increased ventilation. An individual's posture determines the position of the diaphragm. In



• **Fig. 2.2A** A typical rib, angle of the rib. (From *Gray's Anatomy for Students*. 4th ed., published 2020: figure 3.21.)

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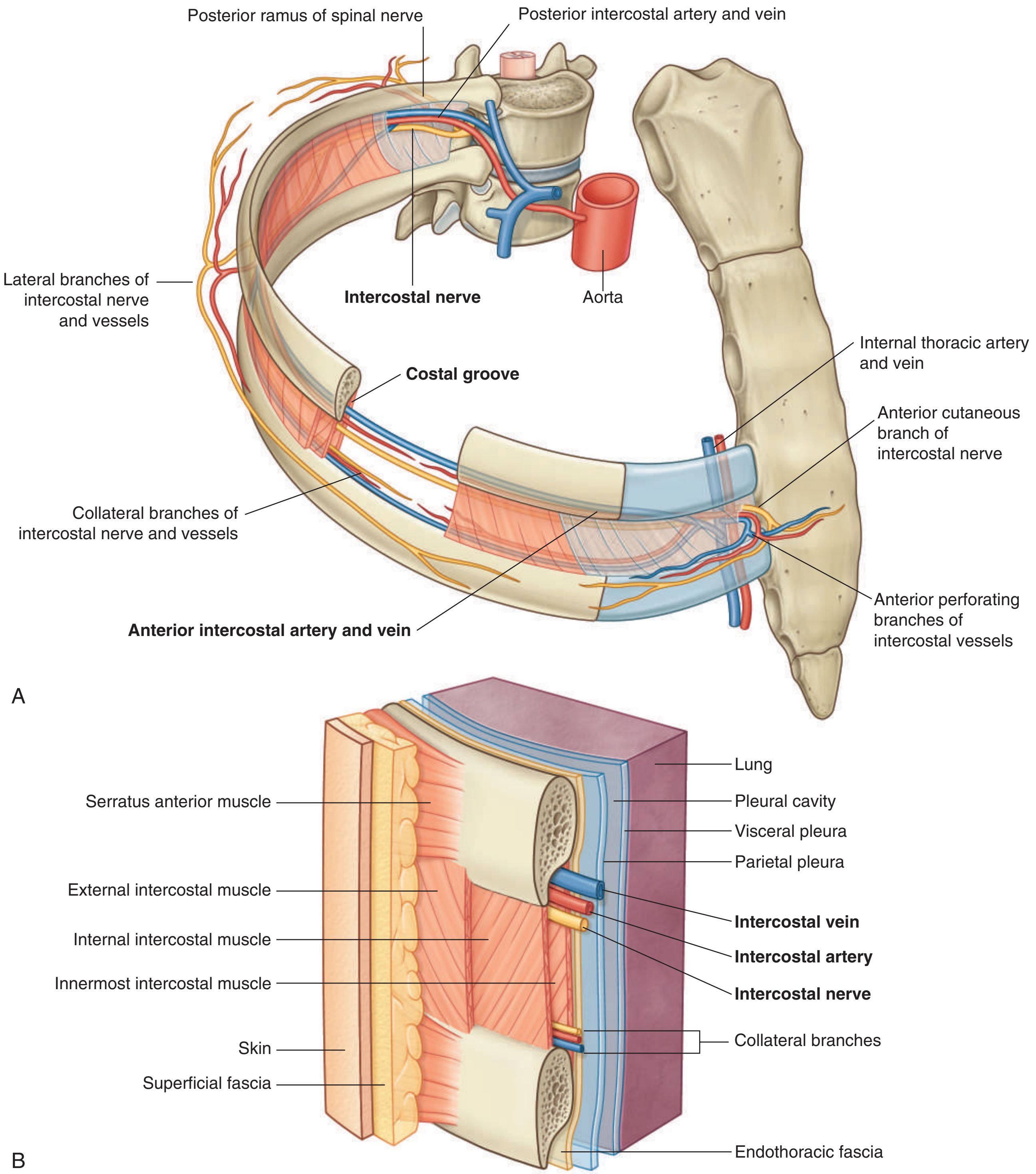
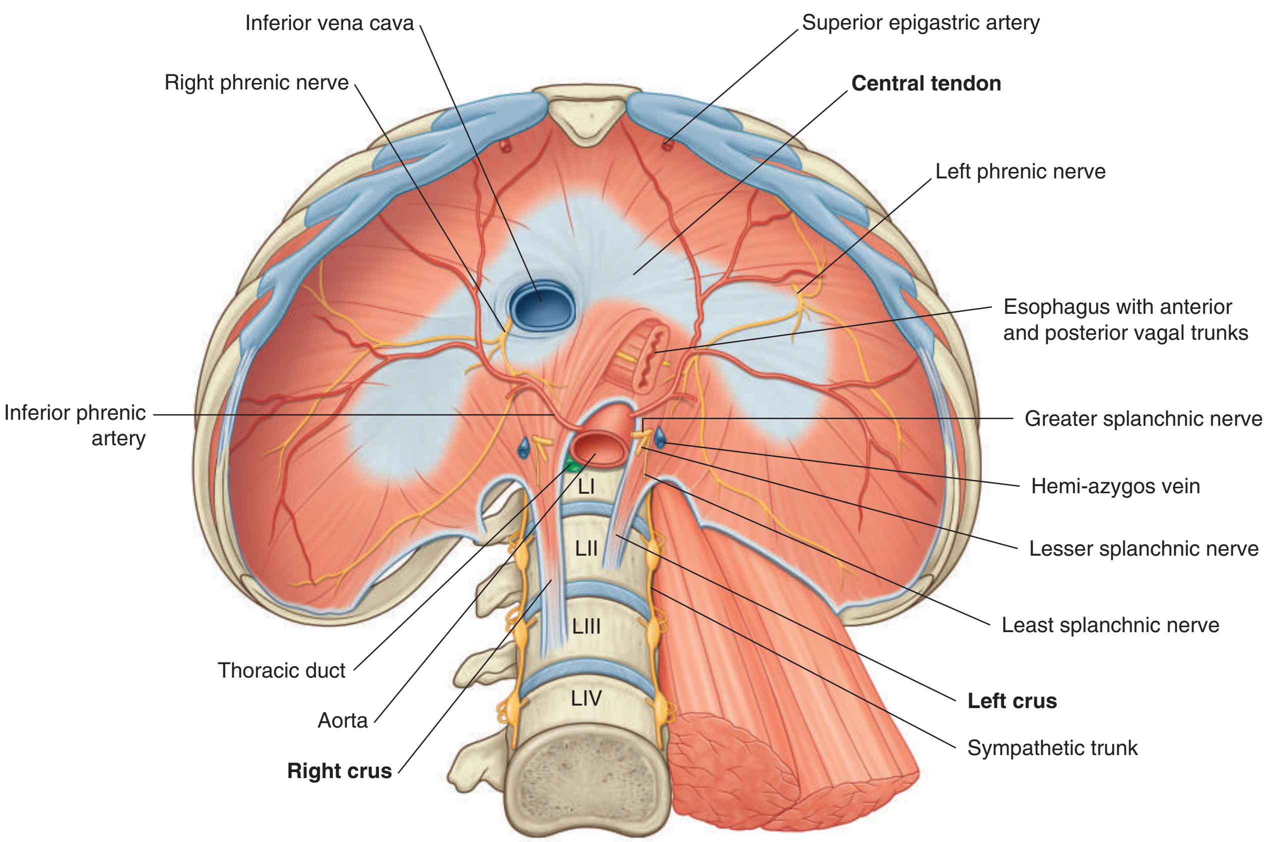
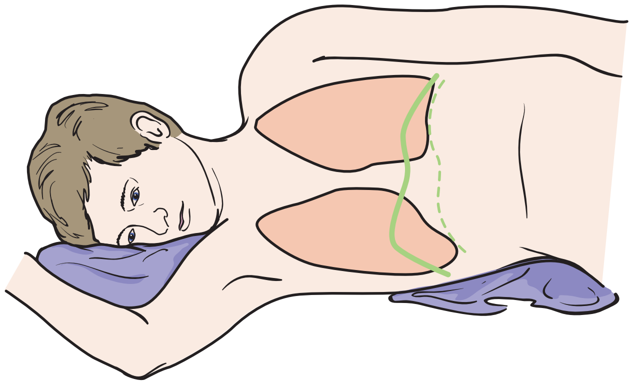


• **Fig. 2.2B** *A,* Intercostal vessels; *B,* nerves. (From *Gray's Anatomy for Students.* 4th ed., published 2020: figure 3.26B.)

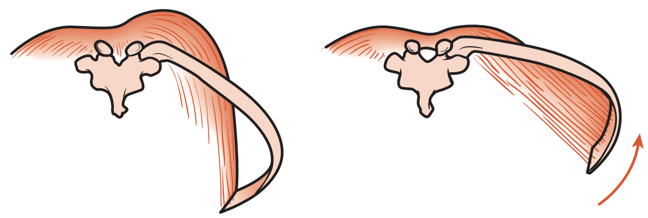
the supine position, the resting level of the diaphragm rises. The greatest respiratory excursions during normal breathing occur in this position; however, the lung volumes are decreased because of the elevated position of the abdominal organs within the thoracic cavity. In a sitting or upright position, the dome of the diaphragm is pulled down by the abdominal organs, allowing a larger lung volume. For this reason, individuals who are short of breath are more comfortable sitting than reclining. In a side-lying position, the dome of the diaphragm on the lower side rises farther into the thorax than the dome on the upper side (Fig. 2.4). The abdominal organs tend to be displaced forward in a side-lying position, allowing greater excursion of the dome on the lower side. In contrast, the upper side moves little with respiration. On radiograph, the position of the diaphragm can indicate whether the film was taken during inspiration or expiration and may also indicate pathology in the lungs, pleurae, or abdomen.



• **Fig. 2.3** Diaphragm. (From *Gray's Anatomy for Students*, 4th ed., published 2020: figure 4.143.)



• **Fig. 2.4** Diaphragm relationships.



• **Fig. 2.5** Action of the diaphragm.

Each half of the diaphragm is innervated by the phrenic nerve on that side. Although the halves contract simultaneously, it is possible for half of the muscle to be paralyzed without affecting the other half. Generally, the paralyzed half remains at the normal level during rest. With deep inspiration, however, the paralyzed half is pulled up by the negative pressure in the thorax.

Contraction of the diaphragm increases the thoracic volume vertically and transversely. The central tendon is drawn down by the diaphragm as it contracts. As the dome descends, abdominal organs are pushed forward as far as the abdominal walls will allow. When the dome can descend no farther, the costal fibers of the diaphragm contract to increase the thoracic diameter of the thorax. This occurs because the fibers of the costal part of the diaphragm run vertically from their attachment at the costal margin: contraction of these fibers elevates and everts the ribs (Fig. 2.5). If the diaphragm is in a low position, it will change the angle of pull of the muscle's costal fibers. Contraction of these fibers creates a horizontal pull, which causes the lateral diameter to become smaller as the ribs are pulled in toward the central tendon.

As the diaphragm descends, it compresses the abdominal organs, increasing intraabdominal pressure. At the same time, the intrathoracic pressure decreases as the lung volume is increased by the descending diaphragm. Inspiratory airflow occurs as a result of this decrease in intrathoracic pressure. The pressure gradient between the abdominal and thoracic cavities also facilitates the return of blood to the right side of the heart.

Movement of the diaphragm can be controlled voluntarily to some extent. Vocalists spend years learning to manipulate their diaphragms so they can produce controlled sounds when singing.

The diaphragm momentarily ceases movement when a person holds his or her breath. The diaphragm is involuntarily involved in parturition; bearing down in bowel movements; and laughing, crying, and vomiting. Hiccups are spasmodic, sharp contractions of the diaphragm that can indicate disease (e.g., a subphrenic abscess) if they persist.

Intercostals

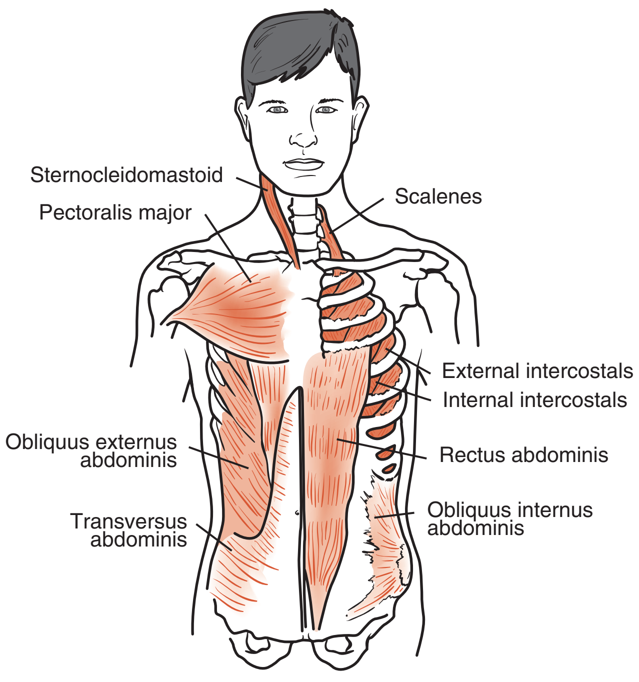
The external intercostals extend down and forward from the tubercles of the ribs (above) to the costochondral junction of the ribs (below), where they become continuous with the anterior intercostal membrane (Fig. 2.6). This membrane extends the muscle forward to the sternum. There are 11 external intercostal muscles on each side of the sternum. They are thicker posteriorly than anteriorly and thicker than the internal intercostal muscles. They are innervated by the intercostal nerves, and contraction draws the lower rib up and out toward the upper rib. This action increases the volume of the thoracic cavity.

There are 11 internal intercostals on each side. These are considered primarily expiratory in function. The intercartilaginous or parasternal portion of the internal intercostals contracts with the external intercostals during inspiration to help elevate the ribs. In addition to their respiratory functions, the intercostal muscles contract to prevent the intercostal spaces from being drawn in or bulged out during respiratory activity.

Sternocleidomastoid

The SCM muscles are strong neck muscles with two heads: one from the manubrium and one from the medial part of the clavicle (see Fig. 2.6). These two heads fuse into one muscle mass that inserts behind the ear into the mastoid process. It is innervated by the accessory nerve and the second cervical nerve. When one SCM contracts, it tilts the head toward the shoulder of the same side and rotates the face toward the opposite shoulder. If the two SCM muscles contract together, they pull the head forward into flexion. When the head is fixed, the muscles assist in elevating the sternum, increasing the anteroposterior diameter of the thorax.

The SCMs are the most important accessory muscles of inspiration. Their contractions can be observed in all patients during forced inspiration and in all patients who are dyspneic. These muscles become visually predominant in patients who are chronically dyspneic.



• **Fig. 2.6** Respiratory muscles: anterior view.

Scalene Muscles

The anterior, medial, and posterior scalene muscles are three separate muscles that are considered a functional unit. They are attached superiorly to the transverse processes of the lower five cervical vertebrae and inferiorly to the upper surface of the first two ribs (see Fig. 2.6). They are innervated by cervical spinal nerves. These muscles are primarily supportive neck muscles, but they can assist in respiration: when their superior attachment is fixed, they act as accessory respiratory muscles and elevate the first two ribs during inspiration.

Serratus Anterior

The serratus anterior arises from the outer surfaces of the first eight or nine ribs. It curves backward, forming a sheet of muscle that inserts into the medial border of each scapula. It is innervated by the long thoracic nerve (C5, C6, and C7). When the scapulae are fixed, the serratus anterior muscles act as accessory respiratory muscles and elevate the ribs to which they are attached.

Pectoralis Major

The pectoralis major is a large muscle arising from the clavicle, the sternum, and the cartilages of all the true ribs (see Fig. 2.6). This muscle spreads across the anterior chest and inserts into the intertubercular sulcus of the humerus. It is innervated by the lateral and medial pectoral nerves (C5–C8, and T1). During forced inspiration when the arms are fixed, it draws the ribs toward the arms, thereby increasing thoracic diameter.

Pectoralis Minor

The pectoralis minor is a thin muscle originating from the outer surfaces of the third, fourth, and fifth ribs near their cartilages. It inserts into the coracoid process of the scapula. It is innervated by the pectoral nerves (C6–C8). During deep inspiration, they contract to elevate the ribs to which they are attached.

Trapezius

The trapezius consists of two muscles that form an extensive diamond-shaped sheet extending from the head down the back and out to both shoulders (Fig. 2.7). Its upper belly originates from the external occipital protuberance, curves around the side of the neck, and inserts into the posterior border of the clavicle. The middle part of the muscle arises from a thin diamond-shaped tendinous sheet, the supraspinous ligaments, and the spines of the upper thoracic region; it then runs horizontally and inserts into the spine of the scapula. Its lower belly arises from the supraspinous ligaments and the spines of the lower thoracic region, runs upward, and inserts into the lower border of the spine of the scapula. This large muscle is innervated by the external or spinal part of the accessory nerve and cervical nerves C3 and C4. Its ability to stabilize the scapulae makes it an important accessory muscle in respiration. This stabilization enables the serratus anterior and pectoralis minor to elevate the ribs.

Erector Spinae

The erector spinae is a large muscle extending from the sacrum to the skull (see Fig. 2.7). It originates from the sacrum, the iliac crest, and the spines of the lower thoracic and lumbar vertebrae. This muscle mass inserts into various ribs and vertebral processes all the way up to the skull. In deep inspiration, these muscles extend the vertebral column, allowing further elevation of the ribs.

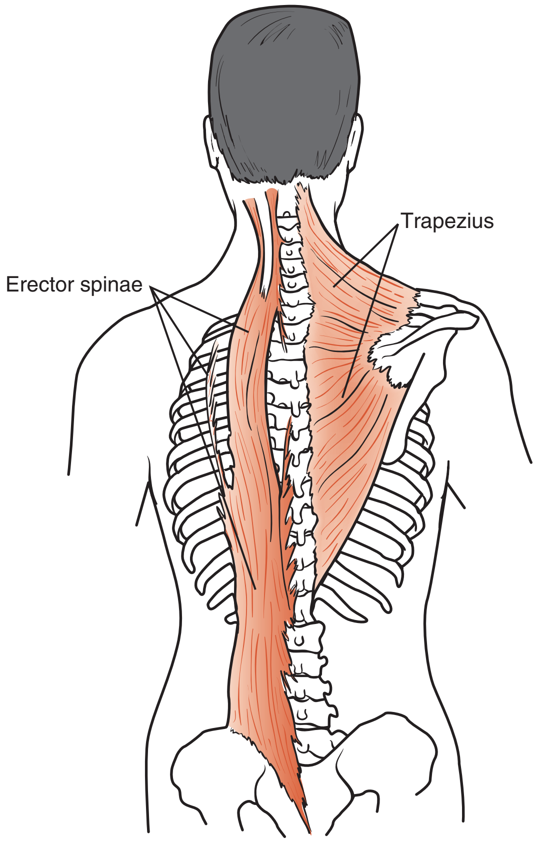
Expiration

Expiration is a passive process that occurs when the intercostals and diaphragm relax. Relaxation of the intercostals and diaphragm allows the ribs to drop to their preinspiratory position and the diaphragm to rise. These activities compress the lungs, which then raises intrathoracic pressure above atmospheric pressure and contributes to airflow out of the lungs. During forced expiration, internal intercostal muscles and abdominal muscles assist in this part of the respiratory cycle.

Action of the Abdominal Muscles

The four muscles of the abdomen (rectus abdominis, internal and external oblique, transversus abdominus) work together to provide a firm but flexible wall to keep the abdominal viscera in position. The abdominal muscles exert a compressing force on the abdomen when the thorax and pelvis are fixed. This force can be used in defecation, urination, parturition, and vomiting. In forced expiration, the abdominal muscles help force the diaphragm back to its resting position and thus force air from the lungs. If the pelvis and vertebral column are fixed, the obliquus externus abdominis aids expiration further by depressing and compressing the lower part of the thorax. Patients with chronic obstructive pulmonary disease (COPD) have difficulty in exhalation, which causes them to trap air in their lungs. The continued contraction of the abdominal muscles throughout exhalation helps them force this air from the lungs. The abdominal muscles also play an important role in coughing. First, a large volume of air is inhaled, and the glottis is closed. The abdominal muscles then contract, raising intrathoracic pressure. When the glottis opens, the large difference in intrathoracic and atmospheric pressure causes the air to be expelled forcefully at tremendous flow rates (tussive blast). Individuals with weak abdominal muscles (from neuromuscular diseases, paraplegia, quadriplegia, or extensive abdominal surgery) often have ineffective coughs.

The four abdominal muscles have many other nonrespiratory functions, both individually and as a group; these functions are not discussed here.



• **Fig. 2.7** Respiratory muscles: posterior view.

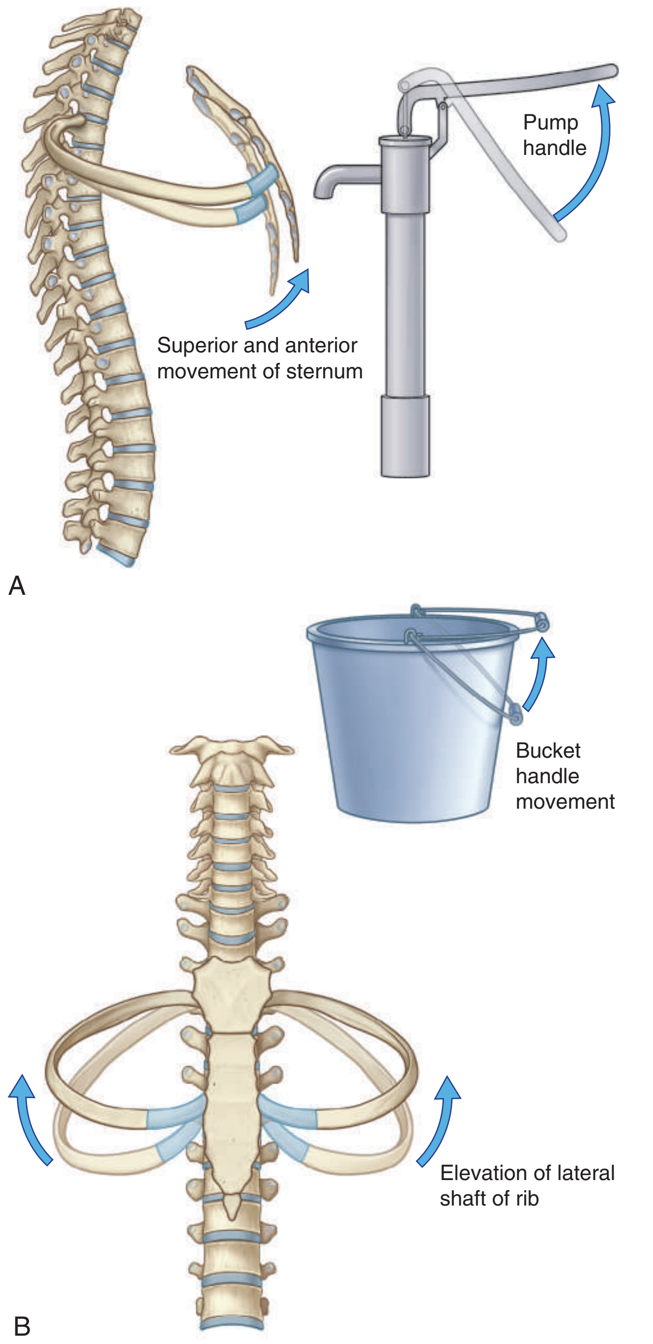
Internal Intercostals

There are 11 internal intercostal muscles on each side of the thorax. Each muscle arises from the floor of the costal groove and cartilage, passes inferiorly and posteriorly, and inserts on the upper border of the rib below. These internal intercostals extend from the sternum anteriorly, around the thorax to the posterior costal angle. They are generally divided into two parts: the interosseous portion, located between the sloping parts of the ribs, and the intercartilaginous portions, located between costal cartilages. Contraction of the interosseous portions of the intercostals depresses the ribs and may aid in forceful exhalation. The intercartilaginous portion, on the other hand, is considered inspiratory in function. These muscles are innervated by the adjacent intercostal nerves.

The Mechanics of Breathing

During quiet inspiration, the diaphragm, external intercostals, and intercartilaginous portions of the internal intercostals are the primary muscles that contract. The diaphragm contracts first and then descends, enlarging the thoracic cage vertically. When the abdominal contents prevent further descent of the diaphragm, the costal fibers of the diaphragm contract, which causes the lower ribs to swing up and out to the side; this is described as the bucket-handle movement (Fig. 2.8). This lateral rib movement is assisted by the external intercostals and the intercartilaginous portion of the internal intercostals. The transverse diameter of the thorax is increased by this bucket-handle movement. Finally, the upper ribs move forward and upward; this is referred to as pump-handle movement (see Fig. 2.8), also through contraction of their external intercostals and the intercartilaginous portions of the internal intercostals. This increases the anteroposterior diameter of the thorax. The epigastric area protrudes, then the ribs swing up and out laterally, and finally the upper ribs move forward and upward.

The inner wall of the thorax, which is lined with parietal pleura, and the parenchyma of the lung, which is enclosed in visceral pleura, lie close to each other. The pleurae are separated by a potential space containing a small amount of pleural fluid. Muscular contraction of the intercostals and the diaphragm mechanically enlarges the thorax. The lungs are enlarged at this time because of their close proximity to the thorax. The healthy lung resists this enlargement and tries to pull away from the chest wall.



• **Fig. 2.8** Movements of the bony thorax in breathing: Pump handle **(A)** and bucket handle **(B)** movements. (From *Gray's Anatomy for Students*, 4th ed., published 2020: figure 3.35.)

Quiet expiration is passive and involves no muscular contraction, although some electrical activity can be detected with electromyography. The inspiratory muscles relax, which raises intrathoracic pressure as the ribs and diaphragm return to their preinspiratory positions and compress the lungs. This increased pressure allows airflow from the lungs.

During forced inspiration, an additional number of accessory muscles may contract along with the muscles involved in quiet inspiration. The erector spinae contract to extend the vertebral column. This extension permits greater elevation of the ribs during inspiration. Various back muscles (e.g., erector spinae, trapezius, and rhomboids) contract to stabilize the vertebral column, head, neck, and scapulae. This enables accessory respiratory muscles to assist inspiration through reverse action. The SCM raises the sternum. The scalenes elevate the first two ribs. The serratus anterior, pectoralis major, and pectoralis minor assist bilateral elevation of the ribs. All these accessory muscles tend to elevate the ribs, thus increasing the anteroposterior diameter, but not the transverse diameter, of the thorax. (The transverse diameter does increase slightly as a result of the increased strength of the contraction of the normal inspiratory muscles.) The marked increase in anteroposterior diameter in relation to transverse diameter creates an impression of en bloc breathing in a patient using accessory muscles.

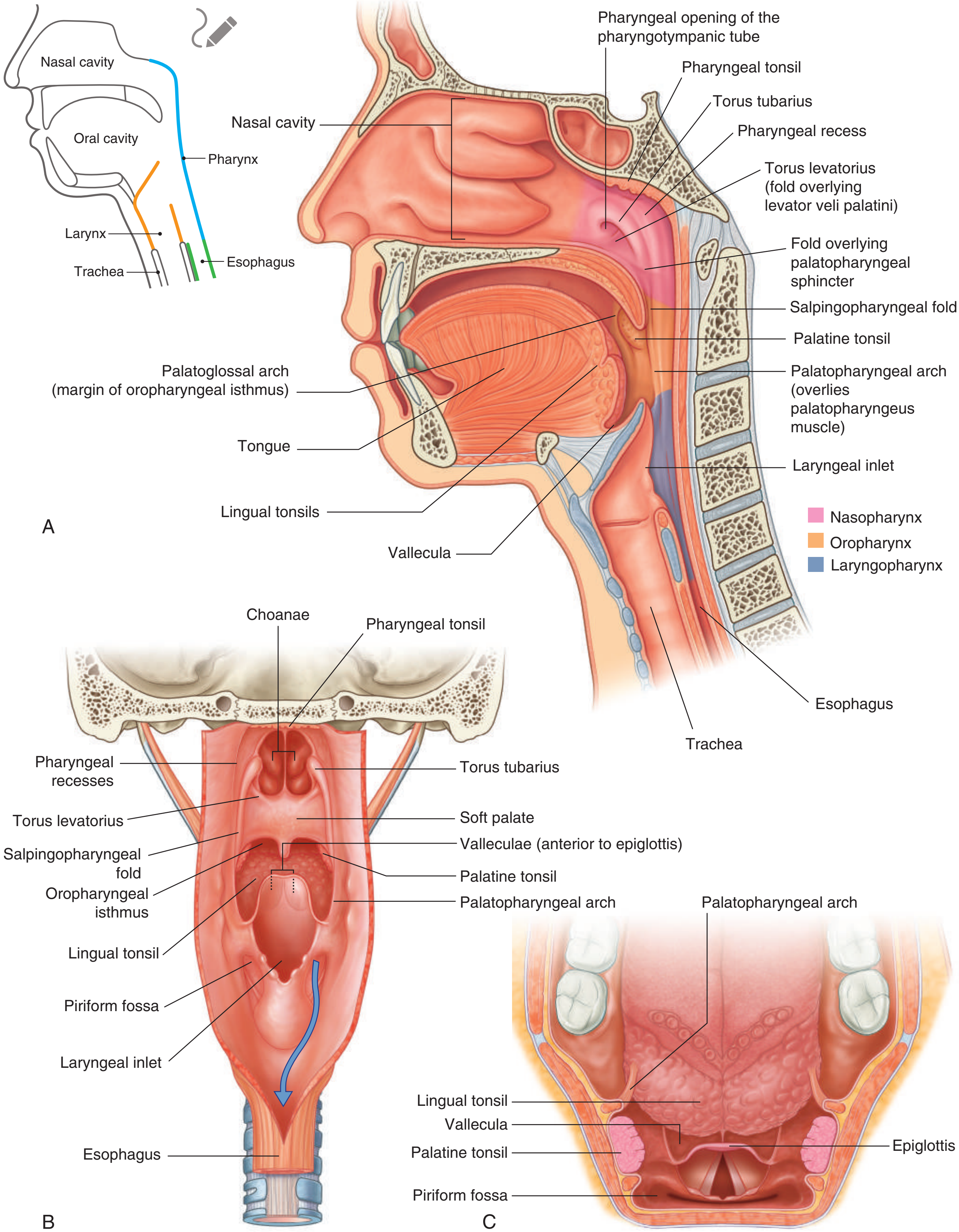
During forced expiration, the interosseous portion of the internal intercostals and the abdominal muscles contract to force air out of the lungs. Forced expiration can be slow and prolonged (as in patients with COPD) or rapid and expulsive (as in a cough). If the abdominal contractions are strong enough, the trunk flexes during exhalation. This flexion further compresses the lungs, forcing more air from them.

Upper Airways

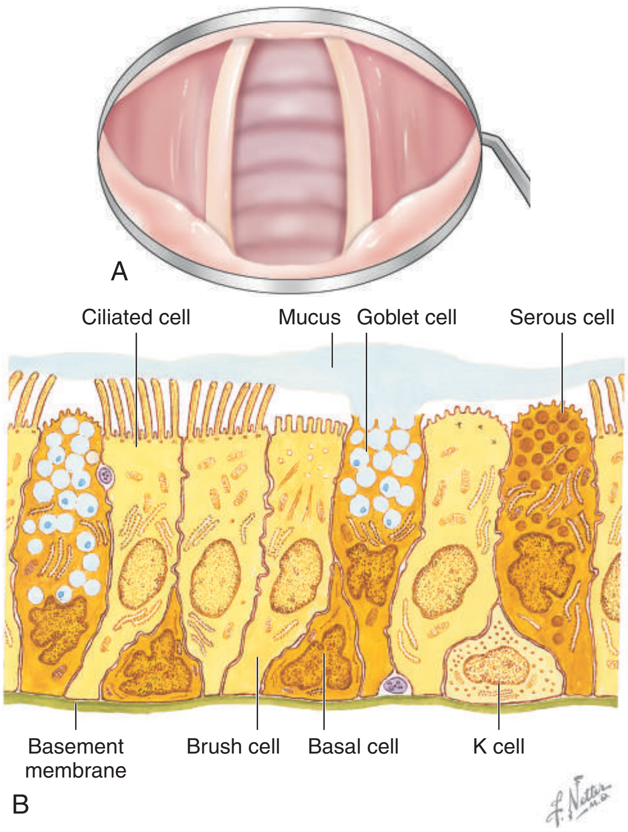
Nose

Noses vary in size and shape among individuals. The nose is composed of bony and cartilaginous parts. The upper one-third is primarily bony and contains the nasal bones, the frontal processes of the maxillae, and the nasal part of the frontal bone. Its lower two-thirds are cartilaginous and contain the septal, lateral, and major and minor alar nasal cartilages. The nasal cavity is divided into right and left halves by the nasal septum. This cavity extends from the nostrils to the posterior apertures of the nose in the nasopharynx. The lateral walls of the cavity are irregular as a result of projecting superior, middle, and inferior nasal conchae. There is a meatus located beneath or lateral to each concha through which the sinuses drain. The conchae increase the surface area of the nose for maximum contact with inspired air. The superior conchae and adjacent septal wall are referred to as the *olfactory region*. They are covered with a thin, yellow olfactory mucous membrane consisting of bipolar nerve cells that are olfactory in function. Only a portion of inspired air reaches the olfactory region to provide a sense of smell. When people smell something specific, they sniff. This action lifts the inspired air so that more of it comes into contact with the olfactory region.

The anterior portion (vestibule) of the nasal cavity (Fig. 2.9) is lined with skin and coarse hairs (vibrissae) that entrap inhaled particles. The rest of the cavity and sinuses (with the exception of the olfactory region) are lined with respiratory mucous membrane. This membrane is composed of pseudostratified columnar ciliated epithelium (Fig. 2.10). It contains goblet cells and mucous and serous glands that produce mucus and serous secretions, respectively. These secretions entrap foreign particles and bacteria. This mucus is then swept to the nasopharynx by the cilia at a rate of 5 to 15 mm/min, where it is swallowed or expectorated. The mucous membrane is vascular, with arterial blood supplied by branches of the internal and external carotid arteries. Venous drainage occurs through the anterior facial veins. The mucous membrane is thickest over the conchae. As air is inhaled, it passes around and over the conchae, whose vascular moist surfaces heat,



• **Fig. 2.9** Upper airway: Nasal and oral cavities and pharynx in midsagittal view. (From *Gray's Anatomy for Students,* 4th ed., published 2020: figure 8.205A.)



• **Fig. 2.10** Epithelium in nose. (Part B from *Netter's Essential Histology,* 3rd ed., 2021: section 15.9, inset figure "Ultrastructural schematic: trachea and large bronchi.")

humidify, and filter the inspired air. The mucous membrane may become swollen and irritated as a result of upper respiratory infections and may secrete copious amounts of mucus. Because this membrane is continuous with sinuses, auditory tubes, and lacrimal canaliculi, people with colds often complain of sinus headaches, watery eyes, earaches, and other symptoms. Secretions can be so copious that the nasal passages become completely blocked.

Pharynx

The pharynx is a semicylindrical fibromuscular sac, which connects the nasal and oral cavities and the larynx posteriorly. It is approximately 12 to 14 cm long and extends from the base of the skull to the esophagus below, at the level of the cricoid cartilage opposite the sixth cervical vertebra. The pharynx has three compartments: the nasal cavity (nasopharynx), mouth (oropharynx), and larynx (laryngopharynx). The pharyngeal walls are lined with ciliated respiratory mucous membrane in the nasal portion and with stratified squamous membrane in the oral and laryngeal parts.

The *nasopharynx* is a continuation of the nasal cavities (see Fig. 2.9). It lies behind the nose and above the soft palate. With the exception of the soft palate, its walls are immovable, so its cavity is never obliterated as are the oropharynx and laryngopharynx. The nasopharynx communicates with the nasal cavity anteriorly through the posterior apertures of the nose. It communicates with the oropharynx and laryngopharynx through an opening, the pharyngeal isthmus, which is closed by elevations of the soft palate during swallowing.

The *oropharynx* extends from the soft palate to the epiglottis (see Fig. 2.9). It opens into the mouth anteriorly through the oropharyngeal isthmus. Its posterior walls lie on the bodies of the second and third cervical vertebrae. Laterally, two masses of lymphoid tissue, the palatine tonsils, may be seen. These tonsils form part of a circular band of lymphoid tissue surrounding the opening into the digestive and respiratory tracts.

The *laryngopharynx* lies behind the larynx and extends from the epiglottis above to the inlet of the esophagus below (see Fig. 2.9). The fourth to sixth cervical vertebrae lie behind the laryngopharynx. In front of the laryngopharynx are the epiglottis, the inlet of the larynx, and the posterior surfaces of the arytenoid and cricoid cartilages.

Larynx

The larynx is a complex structure composed of cartilages and cords moved by sensitive muscles (Fig. 2.11). It is located between the trachea and laryngopharynx, for which it forms an anterior wall. With its rapid closure it acts as a sphincteric valve, preventing food, liquids, and foreign objects from entering the airway. It controls airflow and at times closes so that thoracic pressure may be raised and the upper airways cleared by a propulsive cough when the larynx opens. Expiratory airflow vibrates as it passes over the contracting vocal chords, producing the sounds used for speech.

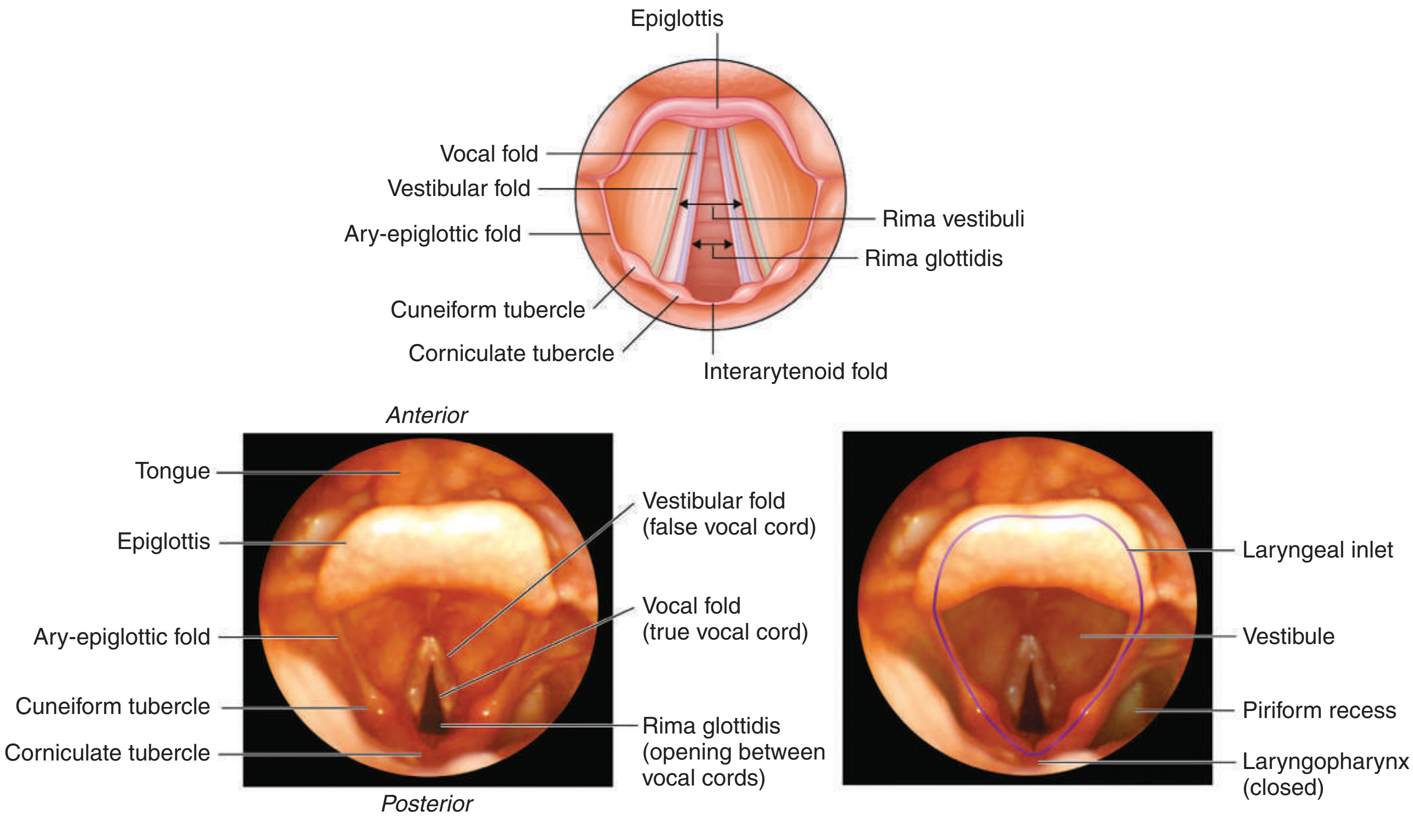
In adult men, the larynx is situated opposite the third, fourth, and fifth cervical vertebrae; it is situated somewhat higher in women and children. The larynx is essentially the same in children, but at puberty, the male larynx increases in size considerably until its anteroposterior diameter has almost doubled. All the cartilages enlarge, and the thyroid cartilage becomes prominent anteriorly.

Vocal cord adductor contraction results in approximation of the vocal cords and narrowing of the glottis. The adductors of the cords are important in protecting the lower airways. Their contraction prevents fluids, food, and other substances from being aspirated. All the intrinsic laryngeal muscles are innervated by the recurrent laryngeal nerve (a branch of the vagus nerve), with the exception of the cricothyroid muscle, which is supplied by the external branch of the superior laryngeal nerve (also a branch of the vagus nerve).

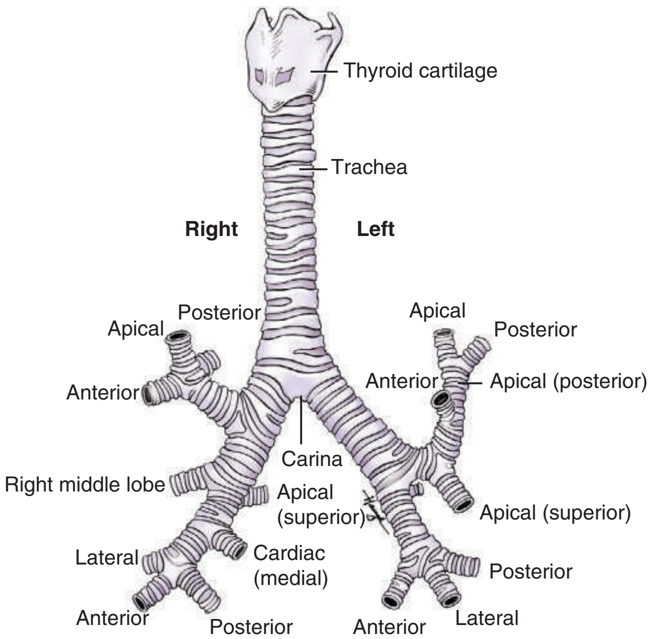
Lower Airways

Trachea

The trachea is a semirigid cartilaginous tube approximately 10 to 11 cm long and 2.5 cm wide. It lies in front of the esophagus and descends with a slight inclination to the right from the level of the cricoid cartilage (Fig. 2.12; see also Fig. 2.11). It travels behind the sternum into the thorax to the sternal angle (opposite the fifth thoracic vertebra), where it divides to form the right and left mainstem bronchi. The tracheal wall is strengthened by 16 to 20 horseshoe-shaped cartilaginous rings. The open parts of the tracheal rings are completed by fibrous and elastic tissue and smooth muscle. This highly flexible part of the ring is positioned posteriorly. It indents or curves inward during coughing, which increases the velocity of expelled air. The cartilaginous rings lie horizontally one above the other, separated by narrow bands of connective tissue. The trachea is lengthened



• **Fig. 2.11** Larynx – visualization with a laryngoscope. (From *Gray's Anatomy for Students,* 4th ed., published 2020: figure 8.221 C&D.)



• **Fig. 2.12** Tracheobronchial tree anatomy.

during hyperextension of the head; during swallowing, which raises the trachea; and during inspiration, when the lungs expand and pull the trachea downward. Its cross-sectional area becomes smaller with contraction of the smooth muscle fibers that complete the tracheal rings.

The mucous membrane of the trachea contains columnar ciliated epithelium and goblet cells. Each ciliated epithelial cell contains approximately 275 cilia. These structures beat rapidly in a coordinated and unidirectional manner, propelling a sheet of mucus toward the head, from the lower respiratory tract to the pharynx, where it is swallowed or expectorated. The cilia beat in this layer of mucus with a forceful forward stroke followed by an ineffective backward stroke that returns the cilia to their starting position. Mucociliary escalation propelling of mucus by the cilia toward the upper trachea for clearance is essential. When cilia are paralyzed by smoking, alcohol, dehydration, anesthesia, starvation, or hypoxia, mucus begins to accumulate in distal, gravity-dependent airways, causing infiltrates and eventually localized areas of lung collapse referred to as *atelectasis*.

The number of mucus-containing goblet cells is approximately equal to the number of ciliated epithelial cells. Reserve cells lie beneath the ciliated and goblet cells. These reserve cells can differentiate into either goblet cells or ciliated cells. Beneath the reserve cells lie the gland cells. There are approximately 40 times more gland cells than goblet cells.

Mucus is composed of 95% water, 2% glycoprotein, 1% carbohydrate, trace amounts of lipid, deoxyribonucleic acid (DNA), dead tissue cells, phagocytes, leukocytes, erythrocytes, and entrapped foreign particles. Mucus lines the airways from the trachea to the alveoli. Two separate layers have been observed: the sol layer, which lies on the mucosal surface and contains high concentrations of water, and the gel layer, which is more superficial and viscous because of its lower concentration of water.

The right mainstem bronchus is an extension of the trachea and is wider, shorter, and more vertical than the left mainstem bronchus.