The Anatomy and Physiology of the Respiratory System

CHAPTER 1

INTRODUCTION

The respiratory system, sometimes referred to as the respiratory tract, plays a critical role in sustaining life by facilitating the exchange of oxygen and carbon dioxide, a process essential for cellular metabolism and overall homeostasis. Comprised of the upper and lower airways, lungs and associated structures, the respiratory system works in harmony with other physiological processes to maintain adequate oxygenation and acid–base balance. A thorough understanding of its anatomy and physiology is fundamental as it provides the foundation for safe, effective and evidence-based patient care.

In clinical practice, knowledge of normal respiratory function is essential for identifying and responding to pathological changes. Many respiratory conditions, such as chronic obstructive pulmonary disease (COPD), asthma, pneumonia and acute respiratory distress syndrome (ARDS), arise from disruptions to normal respiratory mechanics, gas exchange or regulatory mechanisms. Understanding the anatomical and physiological basis of these changes is critical in recognising early warning signs, interpreting clinical findings and implementing appropriate interventions.

In COPD, airway inflammation, mucus hypersecretion and structural remodelling lead to airflow obstruction and impaired gas exchange. Without an understanding of these pathophysiological mechanisms, those who offer care and support to people may struggle to assess respiratory distress accurately, initiate timely interventions such as bronchodilator therapy or oxygen support or educate patients on disease management. Similarly, in conditions such as pneumonia, knowledge of the anatomical location of infection and its impact on ventilation-perfusion matching is crucial for guiding treatment decisions and monitoring progression.

Additionally, pathophysiological changes in the respiratory system often have systemic consequences (Heuer 2021). Hypoxia, hypercapnia and acid–base imbalances can affect multiple organ systems, leading to complications such as cardiovascular strain, cognitive impairment and multi-organ dysfunction. Therefore, an in-depth understanding of both normal and abnormal respiratory function equips healthcare providers with the ability to anticipate complications, make informed clinical decisions and provide holistic patient care.

This chapter will explore the key anatomical components of the respiratory system, including the upper and lower airways, lungs and associated structures, as well as their physiological roles in ventilation and gas exchange. It will also examine how the respiratory system interacts with other body systems, particularly the cardiovascular system, to maintain acid–base balance and overall systemic function.

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By the end of this chapter, readers will have developed an understanding of how the respiratory system operates in health and how its dysfunction manifests in disease. This knowledge will enable them to contribute to high-quality, patient-centred respiratory care, ensuring safety, efficacy and improved patient outcomes in a range of clinical settings.

THE RESPIRATORY SYSTEM

The respiratory system is one of the major systems of the body and is divided into the upper respiratory tract and the lower respiratory tract. Each section plays a critical role in ensuring the proper flow of air and gas exchange (see Figure 1.1).

The upper respiratory tract consists of the nasopharynx and the larynx (above the vocal cords), primarily responsible for filtering, warming and humidifying inhaled air before it reaches the lungs. The lower respiratory tract begins at the larynx (below the vocal cords) and includes the trachea, bronchi and lungs, facilitating the conduction of air and enabling gas exchange.

Located within the thoracic cavity, the respiratory system plays a vital role in maintaining oxygen supply and carbon dioxide removal, essential for cellular metabolism and homeostasis. As air is drawn in through the upper airways, it travels down the trachea and bronchi, branching into progressively smaller bronchioles before reaching the alveoli, the primary sites of gas exchange. Here, oxygen diffuses into the bloodstream, while carbon dioxide is expelled from the body through exhalation. This intricate process ensures adequate oxygenation of tissues while maintaining acid–base balance, crucial for overall physiological function.

THE UPPER RESPIRATORY TRACT

The upper respiratory tract consists of the mouth, nose, nasal cavity and pharynx, which work together to warm, filter and humidify inhaled air before it reaches the lower airways.

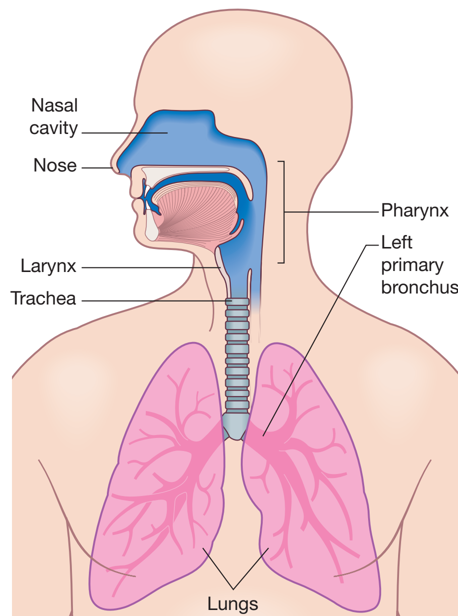

FIGURE 1.1 The respiratory system. *Source*: Peate and Nair (2014). With permission of John Wiley & Sons.

The nasal cavity is divided into two equal sections by the nasal septum, a structure composed of the ethmoid bone and vomer of the skull. The initial entry point for air into the nasal cavity, just inside the nostrils, is known as the vestibule.

Within the nasal cavity, air flows through three passageways known as the meatuses, which are created by three bony projections: the superior, middle and inferior conchae (or turbinates). These structures increase surface area and create turbulence, allowing incoming air to swirl and bounce off the conchae. This movement helps trap small particles in the nasal mucosa, filtering out debris and pathogens before the air continues towards the lungs.

The pharynx is a muscular chamber that serves as a shared passage for both the respiratory and digestive systems, connecting the nasal and oral cavities to the larynx. It is divided into three distinct regions:

1. The nasopharynx, located behind the nasal cavity, contains two openings that lead to the auditory (Eustachian) tubes, which help regulate middle ear pressure.
2. The oropharynx, situated below the nasopharynx and behind the oral cavity, serves as a passage for both air and ingested materials.
3. The laryngopharynx, the lowest section, continues this dual function, directing air towards the larynx and food towards the oesophagus.

To protect against mechanical abrasion from food and drink, the oropharynx and laryngopharynx are lined with non-keratinised stratified squamous epithelium, which provides a resilient yet flexible barrier. Figure 1.2 provides details of the upper respiratory tract.

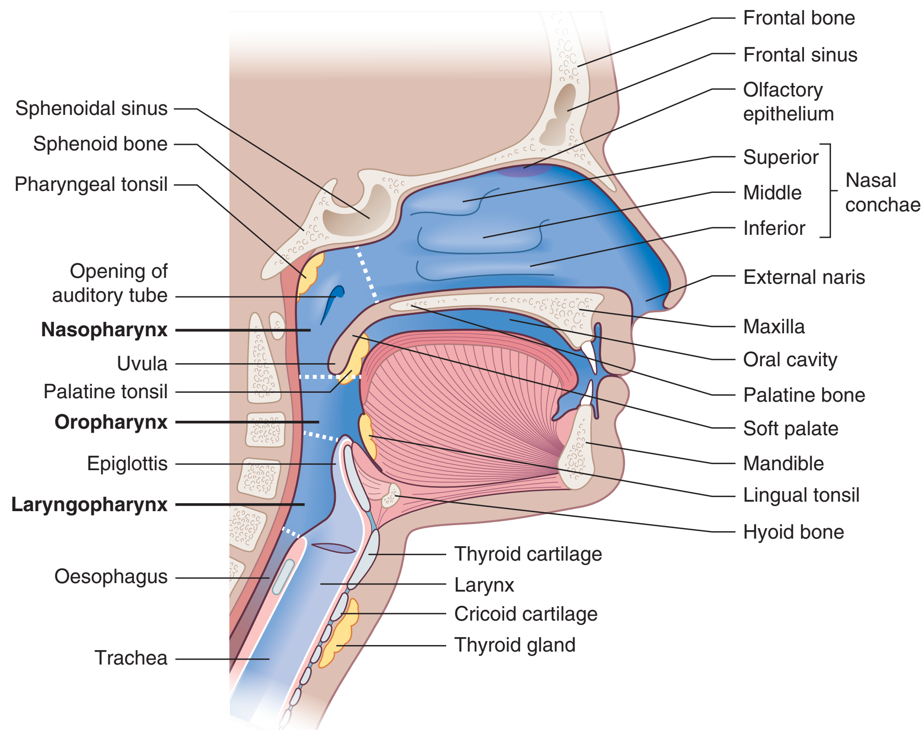

FIGURE 1.2 Details of the structures of the upper respiratory tract. *Source*: Peate and Nair (2014). With permission of John Wiley & Sons.

THE LOWER RESPIRATORY TRACT

The lower respiratory tract consists of the larynx, trachea, right and left primary bronchi and all structures within the lungs. The lungs, two cone-shaped organs, occupy most of the thoracic cavity and are safeguarded by the thoracic cage, which is formed by the ribs, sternum (breastbone) and vertebrae (spine). The airways are lined with a mucous membrane composed primarily of ciliated epithelium, which plays a key role in maintaining airway hygiene. The cilia constantly move mucus and trapped foreign particles upwards towards the throat, where they can be swallowed or expelled.

Larynx

The larynx (voice box) is a cartilaginous structure composed of nine pieces of cartilage: three single cartilages and three paired cartilages. The thyroid cartilage (commonly known as the Adam's apple) and the cricoid cartilage provide structural support and protection for the vocal cords. The epiglottis, a leaf-shaped piece of elastic cartilage, plays a crucial role in airway protection by covering the laryngeal opening during swallowing, directing food and fluids towards the oesophagus to prevent aspiration.

Trachea

The trachea (windpipe) extends from the laryngopharynx, beginning at the level of the cricoid cartilage and continues down to the carina, a ridge-shaped structure where the trachea bifurcates into the left and right main bronchi. The trachea is reinforced by 15–20 C-shaped cartilage rings, which prevent airway collapse or excessive expansion due to pressure changes during breathing. The carina, located around the level of the sixth or seventh thoracic vertebra (T6–T7), contains sensory nerve endings that trigger a cough reflex when foreign substances enter the airway.

Bronchi and bronchioles

At the carina, the trachea divides into two main bronchi:

- The right main bronchus is shorter, wider and more vertical, making it more susceptible to aspiration of foreign objects. It branches into three lobar bronchi (one for each lobe of the right lung).
- The left main bronchus is longer and more angled, branching into two lobar bronchi (one for each lobe of the left lung).

Each lobar bronchus further subdivides into segmental bronchi, which continue branching into progressively smaller bronchi and bronchioles. These, in turn, give rise to terminal bronchioles, followed by respiratory bronchioles, which eventually lead to tiny air sacs that are known as alveoli – the primary sites of gas exchange.

Lungs

The lungs are divided into distinct regions that are called lobes:

- The right lung has three lobes (upper, middle and lower).
- The left lung has two lobes (upper and lower), as well as an indentation known as the cardiac notch, which accommodates the heart.

Each lung is encased by a double-layered pleural membrane:

- The parietal pleura lines the inner surface of the thoracic cavity.
- The visceral pleura directly covers the lungs.

Between these layers lies the pleural space, a narrow cavity that contains pleural fluid, which serves two essential functions:

1. Lubrication: Reducing friction between the pleural layers, allowing smooth expansion and contraction of the lungs during respiration.
2. Surface tension: Helping the pleural layers adhere together, facilitating lung inflation during breathing.

Together, these structures ensure efficient airflow and gas exchange, playing a fundamental role in maintaining oxygen delivery and carbon dioxide removal.

The lower respiratory tract is detailed in Figure 1.3.

The lungs are supplied with blood from multiple arterial sources. The conducting airways receive oxygenated blood from capillaries that branch off the bronchial arteries, which

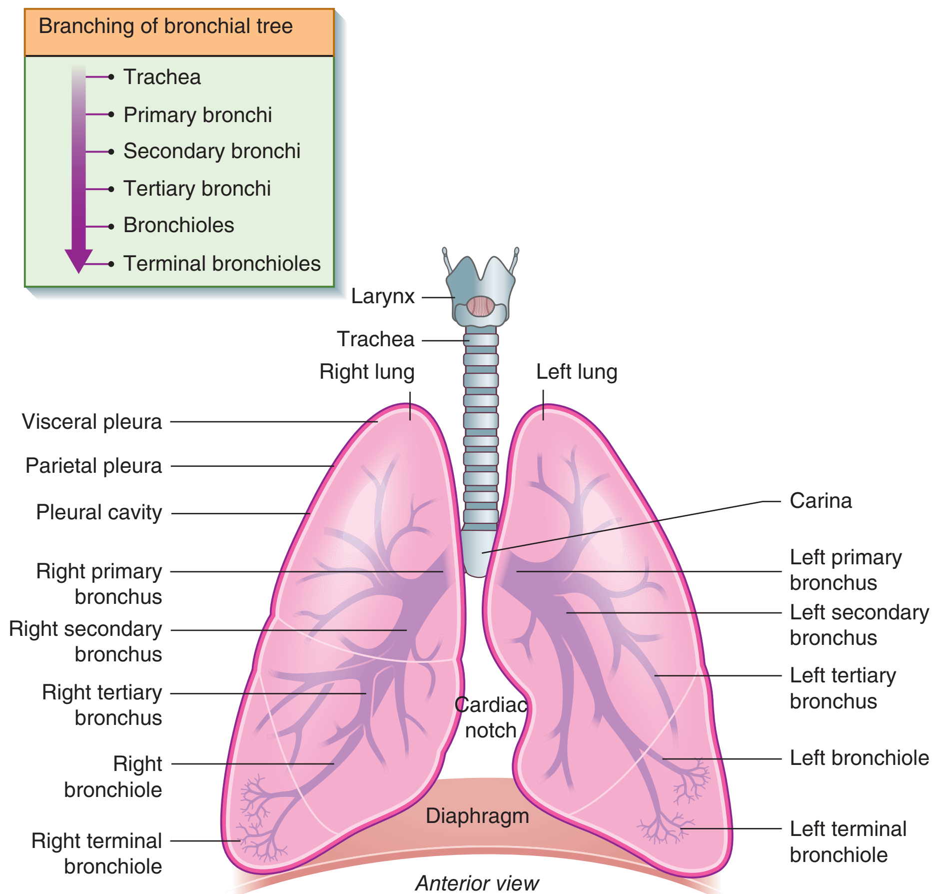

FIGURE 1.3 The lower respiratory system. *Source*: Peate (2020). With permission of John Wiley & Sons.

originate from the aorta. While some bronchial arteries form connections with the pulmonary arteries, most of the blood is drained back to the heart through the pulmonary veins or bronchial veins.

PULMONARY VENTILATION

The primary role of the respiratory system is to deliver oxygen to the body's cells and remove carbon dioxide, ensuring optimal cellular function. Respiration consists of four key processes:

1. Pulmonary ventilation: This is the movement of air into and out of the lungs, continuously refreshing the gases present and is commonly referred to as breathing.
2. External respiration: The exchange of gases occurs between the lungs and the blood, where oxygen moves into the bloodstream and carbon dioxide is expelled into the lungs. This is also known as gaseous exchange.
3. Transport of respiratory gases: The circulatory system transports oxygen from the lungs to body tissues and carries carbon dioxide from the tissues back to the lungs.
4. Internal respiration: This is the transfer of oxygen from the blood into cells and the removal of carbon dioxide from the cells into the bloodstream (Marieb and Keller 2022).

Pulmonary ventilation or breathing, therefore, is the process of moving air in and out of the lungs. Its primary function is to ensure that there is adequate alveolar ventilation, which helps to prevent the accumulation of carbon dioxide in the alveoli while ensuring a continuous supply of oxygen to the body's tissues.

Air movement between the atmosphere and the alveoli occurs due to pressure differences that are created by the contraction and relaxation of the respiratory muscles. The efficiency of this process is influenced by factors such as alveolar surface tension and the overall integrity of lung structures.

INSPIRATION

Before inhalation begins, the pressure inside the lungs is equal to atmospheric pressure (this is 760 mmHg or 101.33 kPa). For air to flow into the lungs, intrapulmonary pressure must drop below atmospheric pressure. This is achieved by increasing lung volume, allowing air to move in naturally.

During inspiration, the thoracic cavity expands, thereby causing intrapulmonary pressure to decrease. As a result of this, air flows into the lungs until equilibrium is reached. This process follows Boyle's law, which states that the pressure of a gas is inversely proportional to the volume of its container (see Figure 1.4). In other words, as lung volume increases, intrapulmonary pressure decreases, drawing air into the lungs.

Dalton's law and the mechanisms of inspiration

Dalton's law explains how gases behave in a mixture. It states that each gas in a mixture (such as atmospheric air) exerts its own pressure, called 'partial pressure', in proportion to its concentration in that mixture. The total pressure of the mixture is simply the sum of the individual partial pressures of all the gases present. For example, atmospheric air at sea level consists of:

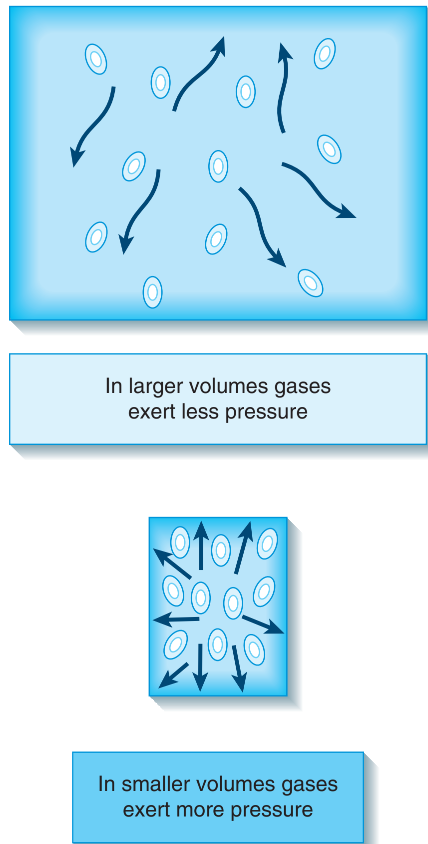

FIGURE 1.4 Boyle's law. *Source*: Peate (2020). With permission of John Wiley & Sons.

- Nitrogen, about 78%
- Oxygen, about 21%
- Other gases (argon, carbon dioxide and so on), about 1%

Since nitrogen makes up the largest portion of air, it exerts the highest partial pressure. The total atmospheric pressure at sea level is 101.33 kPa, meaning nitrogen contributes the most to that pressure, followed by oxygen and the other gases. During inhalation, the thoracic cavity expands, increasing lung volume. This causes intrapulmonary pressure (the pressure inside the lungs) to drop below atmospheric pressure (101.33 kPa at sea level). As gases naturally move from an area of higher pressure to lower pressure, air flows from the atmosphere into the lungs to equalise the pressure difference. This is how oxygen-rich air is breathed in.

Breathing is facilitated by muscles that create pressure changes within the thoracic cavity. There are a variety of respiratory muscles that usually work together to facilitate thoracic expansion during the process of inspiration. The primary muscles involved are the diaphragm and external intercostal muscles. See Figure 1.5 for the muscles involved in pulmonary ventilation.

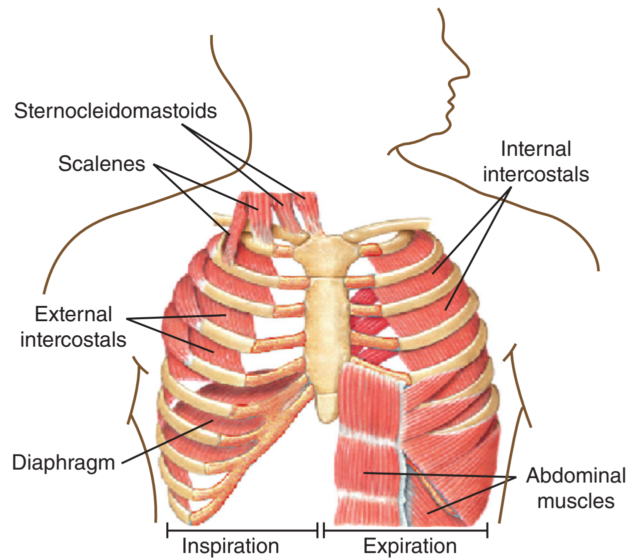

FIGURE 1.5 Muscles involved in pulmonary ventilation. *Source*: Peate (2017). With permission of John Wiley & Sons.

The diaphragm is a dome-shaped skeletal muscle located beneath the lungs at the base of the thorax. The external intercostal muscles consist of 11 pairs situated between the ribs. During inspiration, the diaphragm contracts and moves downwards, creating space for the lungs to expand. Simultaneously, the external intercostal muscles contract, lifting the rib cage outwards and upwards, further increasing thoracic volume. Figure 1.6 illustrates the process of inhalation (inspiration) and exhalation (expiration).

As the thoracic cavity enlarges, intrapulmonary pressure decreases below atmospheric pressure, creating a pressure gradient that allows air to flow into the lungs. The diaphragm is the most significant muscle in this process, accounting for approximately 75% of the air drawn into the lungs during inspiration.

EXPIRATION

Exhalation or breathing out occurs due to a pressure gradient between the lungs and the atmosphere. Unlike inhalation, where air enters the lungs due to a lower intrapulmonary pressure, exhalation happens when the pressure within the lungs exceeds atmospheric pressure, driving air out of the respiratory system.

Passive exhalation

Passive exhalation occurs at rest. Normal exhalation is a passive process that does not require muscle contraction. Instead, it relies on the elastic recoil of the lungs and the chest wall. The alveoli and lung tissues contain elastic fibres that stretch during inhalation. Once the inspiratory muscles have relaxed, these fibres recoil, causing the thoracic cavity to decrease in size. As lung volume decreases, intrapulmonary pressure rises above atmospheric pressure, forcing air out. This passive mechanism ensures that efficient ventilation occurs without excessive energy expenditure.

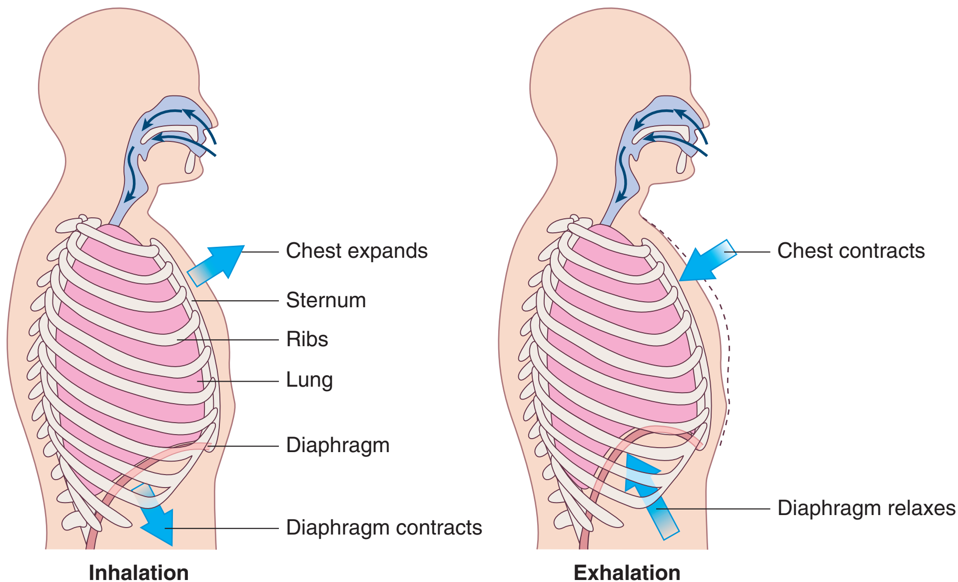

FIGURE 1.6 Inspiration and expiration. *Source*: Peate (2020). With permission of John Wiley & Sons.

Active exhalation

During increased respiratory demand, such as during exercise, physical exertion or respiratory distress, exhalation then becomes an active process. This means that additional muscles are engaged to help force the air out more rapidly and completely. The primary muscles involved in active expiration include:

- Internal intercostal muscles: These muscles lie beneath the external intercostal muscles and pull the ribs downwards and inwards; this results in a reduction in the size of the thoracic cavity.
- Abdominal muscles (rectus abdominis, transverse abdominis, external and internal obliques): These contract to push the abdominal organs upwards against the diaphragm, further decreasing lung volume and increasing intrapulmonary pressure.

This muscular action significantly increases the efficiency of expiration by expelling more air per breath, which is particularly important during intense physical activity, coughing or conditions such as COPD, where airway resistance is increased.

Effective exhalation is essential for maintaining effective gas exchange. It allows for the removal of carbon dioxide (CO_2), a waste product of cellular respiration. An accumulation of CO_2 in the blood can lead to respiratory acidosis, a condition that disrupts the body's acid–base balance. Controlled and efficient expiration ensures that CO_2 levels remain within normal physiological ranges, thereby maintaining homeostasis and preventing respiratory complications.

While passive expiration is sufficient for resting conditions, the ability to engage active exhalation when needed highlights the adaptability and efficiency of the respiratory system as it makes its response to different physiological demands.

FACTORS INFLUENCING PULMONARY VENTILATION

SURFACE TENSION OF ALVEOLAR FLUID

The surface tension in the alveolar fluid is primarily caused by surfactant, a substance made up of phospholipids and lipoproteins that is secreted by type II alveolar cells (see Box 1.1). Surfactant plays a crucial role in reducing the surface tension at the air–liquid interface within the alveoli, which helps prevent alveolar collapse, particularly during exhalation.

BOX 1.1 SURFACTANT

Surfactant is a mixture of fats and proteins made by special cells in the lungs called type II alveolar cells. Its main job is to reduce surface tension inside the alveoli, which are the tiny air sacs in the lungs where oxygen and carbon dioxide are exchanged.

Surface tension is a force that naturally pulls things together, just as water molecules stick to each other. In the lungs, this would make it hard for the alveoli to stay open and take in air. Surfactant reduces this force, making it easier for the alveoli to expand when we breathe in.

When inhalation occurs, surfactant helps the alveoli to open by lowering the surface tension. This allows the lungs to expand with less effort. During exhalation, surfactant also helps the lungs 'shrink' back, pushing air out more easily.

If there is not enough surfactant, as may occur in premature babies or certain lung conditions, the alveoli can collapse, which makes it difficult to breathe and get enough oxygen.

In essence, surfactant helps the lungs expand when breathing in and contract when breathing out. This action makes breathing more efficient and helps the body obtain enough oxygen.

Source: Adapted from Wheeldon (2020) and McCahill (2024).

During inhalation, the lungs must expand to allow for the intake of air, and the surface tension within the alveolar fluid resists this expansion. This resistance is counteracted by surfactant, which reduces the surface tension and makes it easier for the lungs to expand. Without adequate surfactant, the work required for inhalation would be significantly higher and the alveoli would be more prone to collapse due to the high surface tension.

Furthermore, surfactant not only aids in the expansion of the lungs but also contributes to the elastic recoil of the lungs during exhalation. As exhalation occurs, surfactant helps maintain the surface tension at a level that facilitates the passive recoil of lung tissue, expelling air and maintaining optimal lung function.

This balance between surface tension reduction during inhalation and maintenance of lung recoil during exhalation is required for efficient and effective breathing. Inadequate or dysfunctional surfactant production, as seen in conditions such as neonatal respiratory distress syndrome, can lead to difficulty in lung expansion and poor gas exchange, highlighting the importance of surfactant in normal respiratory function.

AIRWAY RESISTANCE

The movement of air in and out of the lungs is influenced by two key factors: resistance and pressure difference. Resistance refers to how much the walls of the airways hinder the airflow and the pressure difference is the force that drives air into and out of the lungs. The walls of the airways naturally create some resistance, which slows down the flow of air.

During inhalation, the bronchioles, the small air passages in the lungs, expand or dilate. This happens because the walls of the bronchioles are pulled in all directions, allowing more space for air to enter the lungs. The size of these airways is also controlled by the smooth muscles around them. These muscles can change the width of the air passages, affecting how much air can flow through.

When the sympathetic nervous system is activated, it sends signals to relax the smooth muscles around the airways. This relaxation causes the bronchioles to widen, a process that is known as bronchodilation. As the airways open up, the resistance to airflow decreases, making it easier for air to move into and out of the lungs. When the sympathetic nerves stimulate the muscles to relax, the airways will dilate, allowing for easier breathing with less resistance.

LUNG COMPLIANCE

Compliance is an important concept in respiratory physiology; it refers to the effort that is required for the expansion of the lungs and chest during breathing. Essentially, lung compliance describes how easily the lungs can stretch and expand when air is drawn in. The higher the compliance, the less effort is needed for lung and chest expansion. In contrast, when there is low compliance, this means that more force is needed to expand the lung, thus making breathing more difficult.

Two primary factors influence lung compliance: surface tension and elasticity.

- Surface tension: Inside the alveoli, surface tension acts like a force that resists lung expansion. The lining of the alveoli tends to pull the walls together, making it harder for the lungs to expand. This resistance is reduced by surfactant. Surfactant reduces the surface tension by interspersing itself between water molecules, preventing the alveolar walls from sticking together. This makes it easier for the lungs to expand during inhalation, thus increasing compliance.
- Elasticity: The lungs contain elastic fibres within their tissues that allow them to stretch and recoil during the breathing process. These elastic fibres help the lungs expand when air is inhaled and return to their original size during exhalation. The more elastic the lung tissue, the more easily the lungs can expand, which contributes to higher compliance.

In healthy, normal lungs, both surface tension and elasticity work together to allow easy expansion. The surfactant lowers surface tension and the elastic fibres stretch easily, meaning less effort is needed to breathe.

In some pulmonary diseases, however, lung compliance can be reduced. One example is emphysema, a condition that is often associated with long-term smoking. In emphysema, the walls of the alveoli are damaged, leading to the loss of many elastic fibres. This loss makes the lungs less elastic, so they cannot stretch as easily. As a result, the lungs become stiffer and more effort is required to breathe. This is a form of decreased compliance, meaning the patient may experience difficulty with both inhalation and exhalation because their lungs are less able to expand and recoil.

In conditions such as pulmonary fibrosis, scar tissue replaces normal lung tissue, which further reduces elasticity and increases the effort needed for lung expansion.

Lung compliance is critical for normal breathing. Healthy lungs have high compliance, requiring less effort to expand and contract, while conditions that damage the lungs or affect their ability to stretch or recoil result in low compliance, which makes breathing more laborious.

LUNG VOLUMES

Lung volumes refer to the different amounts of air that can be inhaled, exhaled or held within the lungs at various stages of the respiratory cycle. These volumes provide insight into lung function and respiratory efficiency and are important for assessing pulmonary health in both healthy individuals and those with respiratory conditions.

NORMAL RESPIRATION AND TIDAL VOLUME

In a healthy resting adult, the typical respiratory rate is 12–20 breaths per minute (Hill and Annesley 2020). Each breath moves approximately 500 mL of air in and out of the lungs. This volume, known as the tidal volume (TV), represents the amount of air exchanged during normal, unforced breathing.

Clinical relevance

In conditions such as respiratory distress syndrome or COPD, TV may decrease due to impaired lung mechanics or airway obstruction, leading to inefficient ventilation and oxygen exchange.

INSPIRATORY RESERVE VOLUME

When a person takes a deep breath beyond the normal TV, they can inhale an additional volume of air (Boyd 2023). This is known as the inspiratory reserve volume (IRV), which is the maximum amount of air that can be drawn into the lungs after a normal inspiration. The IRV varies based on factors such as lung elasticity, chest wall compliance and an individual's physical fitness.

- In adult males, the IRV can be up to 3100 mL.
- In adult females, the IRV is approximately 1900 mL.

Clinical relevance

Reduced IRV is often seen in conditions such as pulmonary fibrosis, where lung stiffness restricts deep inspiration or in neuromuscular disorders, where weakened respiratory muscles limit lung expansion.

EXPIRATORY RESERVE VOLUME

Similarly, after a normal exhalation, it is possible to forcibly exhale additional air from the lungs (Wheeldon 2024). This extra amount of air is called the expiratory reserve volume (ERV).

- In males, ERV is typically 1200 mL.
- In females, ERV is approximately 700 mL.

Clinical relevance

Conditions such as obesity, kyphoscoliosis or restrictive lung diseases can reduce ERV by limiting chest wall mobility and lung deflation.

RESIDUAL VOLUME

Even after a maximal forced exhalation, some air remains in the lungs (Hill and Mutrie 2022). This volume is called the residual volume (RV) and helps prevent lung collapse by keeping the alveoli open.

- In males, RV is approximately 1200 mL.
- In females, RV is around 1100 mL.

Clinical relevance

- In obstructive lung diseases such as emphysema, RV increases due to air trapping in damaged alveoli.
- In restrictive lung diseases, RV may be lower due to reduced lung expansion.

VITAL CAPACITY

This is the total amount of air a person can move in and out of the lungs during forced breathing (Wheeldon 2024). It is calculated as:

$$VC = TV + IRV + ERV$$

In this example, an adult female:

- TV = 500 mL
- IRV = 1900 mL
- ERV = 700 mL

$$VC = 500 + 1900 + 700$$
$$VC = 3100 \text{ mL (or 3.1 L)}$$

Vital capacity (VC) reflects the maximum ventilation ability of the lungs and varies based on age, sex, body size and fitness level.

Clinical relevance

- Reduced VC is common in diseases such as pulmonary fibrosis, muscular dystrophy or severe scoliosis, where lung expansion is restricted.
- Athletes and individuals with high aerobic fitness tend to have a higher VC due to stronger respiratory muscles and better lung compliance.

TOTAL LUNG CAPACITY

Total lung capacity (TLC) is the maximum amount of air the lungs can hold, including all volumes (Preston and Kelly 2016). It is calculated as:

$$TLC = TV + IRV + ERV + RV$$

In this example, an adult male:

- TV = 500 mL
- IRV = 3100 mL
- ERV = 1200 mL
- RV = 1200 mL

$$TLC = 500 + 3100 + 1200 + 1200$$
$$TLC = 6000 \text{ mL (or 6.0 L)}$$

TLC represents the maximum amount of air the lungs can hold after a full inhalation. It varies based on age, sex, height and a person's overall lung health.

Clinical relevance

- TLC is increased in conditions, including emphysema, where lung hyperinflation occurs due to loss of elastic recoil.
- TLC is reduced in conditions such as pulmonary fibrosis or pleural effusion, where lung expansion is mechanically restricted.

Lung volumes are measured using spirometry, a diagnostic tool used in pulmonary function testing. This test helps assess obstructive lung diseases, such as asthma and COPD, where airflow resistance increases, and restrictive lung diseases, such as fibrosis and neuromuscular disorders, where lung expansion is limited.

Understanding lung volumes provides a foundation for assessing respiratory health and diagnosing lung conditions. Recognising normal values and variations due to disease can help to improve the interpretation of pulmonary function tests, monitor disease progression and guide treatment strategies.

REGULATION OF BREATHING

The regulation of breathing is a complex process involving the brainstem, which ensures that oxygen and carbon dioxide levels remain balanced in the body. Several key areas within the brainstem, specifically the pons and medulla oblongata (see Figure 1.7), control the rhythm, depth and rate of respiration. Understanding these mechanisms is crucial for healthcare students, as it helps in recognising and managing respiratory distress in clinical practice.

PNEUMOTAXIC AREA AND ITS ROLE IN RESPIRATORY REGULATION

This area modifies the activity of the dorsal respiratory group. This is the group of nerve cells (neurones) located in the brainstem in the medulla, which controls the inspiratory muscles. When breathing needs to be faster and shallower, the pneumotaxic area signals the dorsal respiratory group to shorten the duration of inspiration. Conversely, when deeper breaths are required, it allows the dorsal respiratory group to prolong its bursts of activity. This coordination ensures that breathing is adjusted to meet the body's oxygen demands during activities such as exercise or stress.

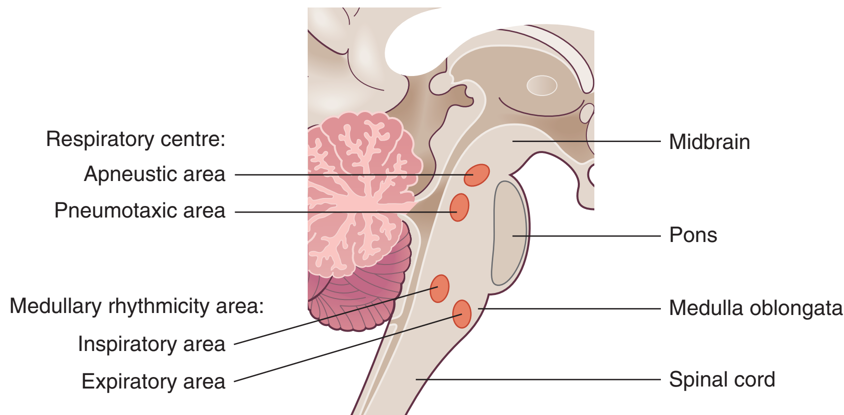

FIGURE 1.7 The respiratory centre. *Source*: Peate (2020). With permission of John Wiley & Sons.

APNEUSTIC AREA

Also located in the pons, the apneustic area plays a role in prolonging inspiration. It stimulates the inspiratory centre, causing deep, sustained breaths. However, its activity is normally overridden by the pneumotaxic area, ensuring that breathing remains regular rather than excessively prolonged.

Medullary rhythmicity area

The medulla oblongata houses the medullary rhythmicity area, which is responsible for maintaining the basic rhythm of breathing. This area contains two distinct groups of neurones:

- The inspiratory centre (dorsal respiratory group): The dorsal respiratory group generates nerve impulses that stimulate the diaphragm and external intercostal muscles, causing inhalation. During quiet breathing, the dorsal respiratory group is active for about two seconds, leading to inspiration, followed by three seconds of inactivity, allowing for passive expiration.
- The expiratory centre (ventral respiratory group): During normal breathing, the ventral respiratory group remains inactive because exhalation is passive. However, during forceful breathing (e.g. during exercise), the ventral respiratory group sends signals to the internal intercostal and abdominal muscles, actively contracting them to force air out of the lungs.

CENTRAL CHEMORECEPTORS

Located in the brainstem, these chemoreceptors play a crucial role in monitoring changes in CO_2 and hydrogen ion (H^+) levels in the cerebrospinal fluid (CSF). Since CO_2 can cross the blood–brain barrier, it mixes with water in the CSF. This reaction creates carbonic acid, which then breaks down into hydrogen ions (H^+).

It is important to note that changes in blood pH alone do not directly stimulate central chemoreceptors because H^+ ions cannot cross the blood–brain barrier. Instead, it is the rise in CO_2 levels that indirectly triggers a response by altering the pH within the CSF.

PERIPHERAL CHEMORECEPTORS

Peripheral chemoreceptors (see Figure 1.8) are located in two main areas:

- Carotid bodies (found at the bifurcation of the common carotid artery)
- Aortic bodies (found in the aortic arch)

These receptors directly detect oxygen levels in the blood. When blood oxygen levels drop (hypoxia), they send signals to the brainstem to increase the respiratory rate, enhancing oxygen intake. Unlike central chemoreceptors, peripheral chemoreceptors respond directly to low oxygen levels, as well as changes in carbon dioxide and pH, making them crucial for responding to acute respiratory challenges.

INFLATION REFLEX

Inflation reflex, also called the Hering–Breuer reflex, prevents overinflation of the lungs. Specialised stretch receptors in the lung tissue detect excessive expansion during deep inhalation. These receptors send signals to the pneumotaxic area, which then inhibits further inspiration, ensuring the lungs do not overinflate. This is an example of a negative feedback mechanism that helps maintain lung function and prevents damage to lung tissue.

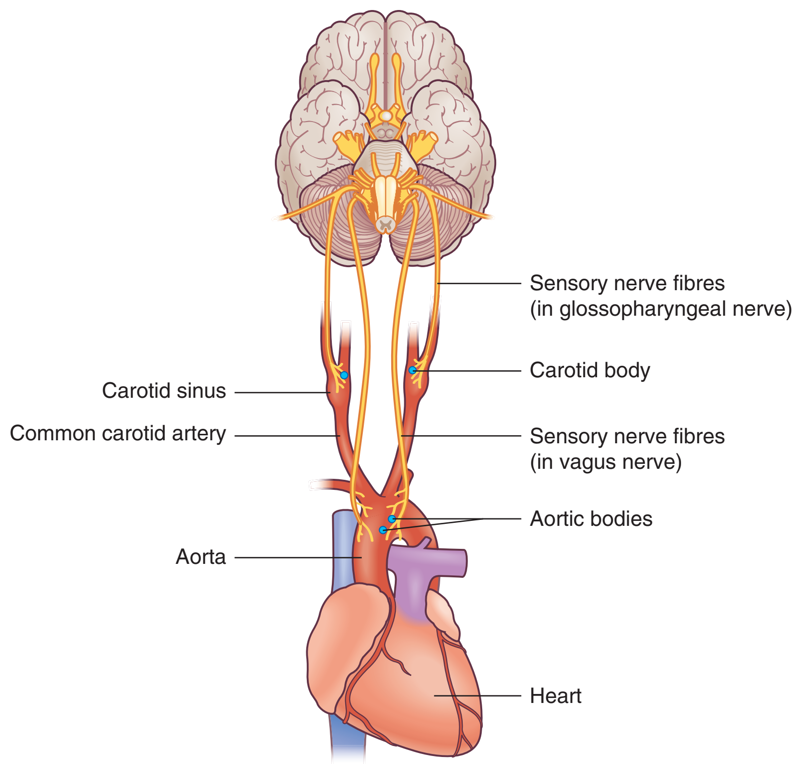

FIGURE 1.8 Peripheral chemoreceptors. *Source*: Peate (2020). With permission of John Wiley & Sons.

Clinical relevance

Understanding the neural and chemical control of respiration is essential, as it provides insight into the mechanisms behind respiratory disorders such as:

- COPD: In this condition, CO_2 builds up in the blood, which can change how the body responds to breathing signals.
- Respiratory acidosis: When breathing is too slow or shallow, CO_2 builds up, which makes the blood more acidic, which can be dangerous.
- Hypoxic drive: Some people with long-term lung diseases rely more on low oxygen levels, rather than high CO_2 levels, to trigger breathing. Giving too much oxygen can reduce their drive to breathe.

Understanding these physiological processes can help ensure that those who offer care and support to people with respiratory conditions will be better equipped to care for patients.

PULMONARY VENTILATION AND GAS EXCHANGE

The main purpose of breathing (pulmonary ventilation) is to ensure a constant supply of fresh air to the lungs, allowing for efficient gas exchange. This process happens in the alveoli, where oxygen moves from the air into the blood and carbon dioxide moves from the blood into the lungs to be exhaled. This exchange occurs through diffusion, where gases move from areas of high concentration to low concentration (see Figure 1.9).

EXTERNAL RESPIRATION (GAS EXCHANGE IN THE LUNGS)

External respiration refers to the transfer of gases between the lungs and the blood. Oxygen moves from the alveoli (tiny air sacs in the lungs) into the surrounding capillaries, while carbon dioxide moves from the blood into the alveoli to be exhaled. This process ensures that the blood leaving the lungs is rich in oxygen before being pumped around the body by the heart.

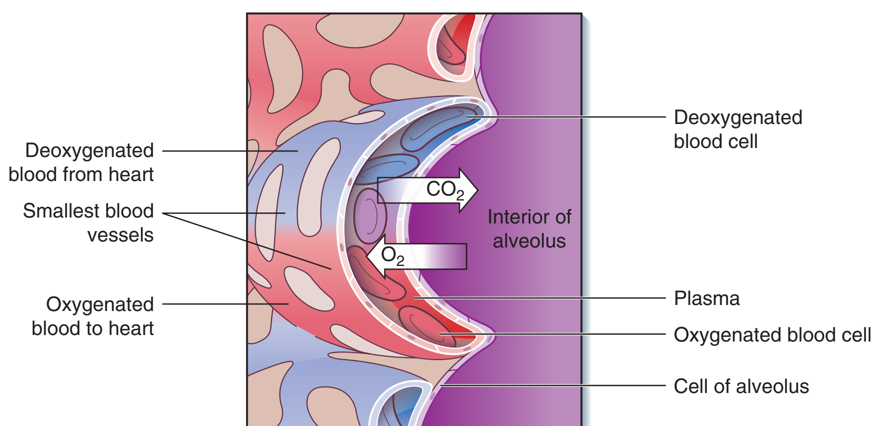

FIGURE 1.9 Gaseous exchange in the lungs. *Source*: Peate (2020). With permission of John Wiley & Sons.

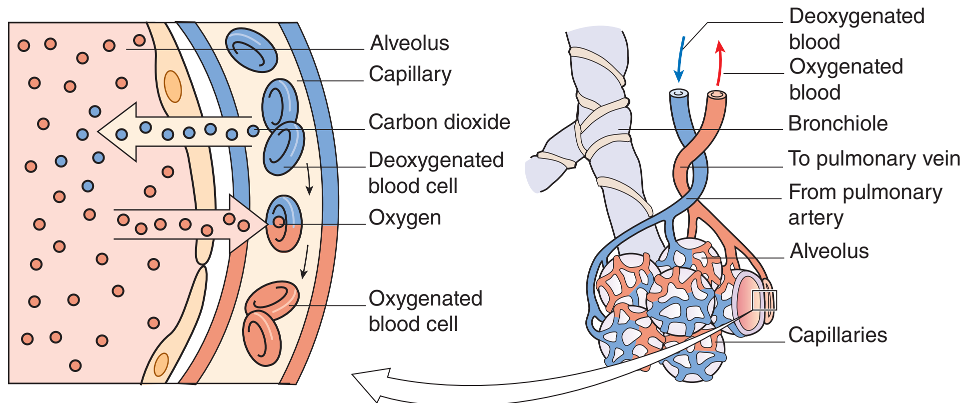

FIGURE 1.10 External respiration. *Source*: Peate and Evans (2020). With permission of John Wiley & Sons.

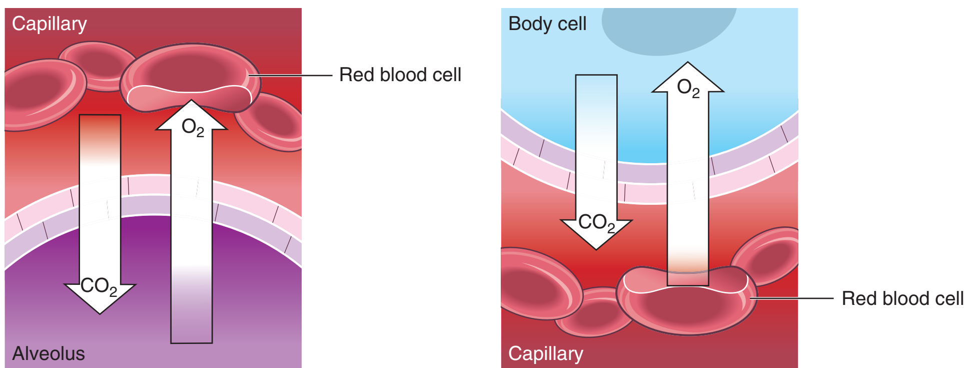

FIGURE 1.11 Internal respiration. *Source*: Peate (2020). With permission of John Wiley & Sons.

External respiration happens only in the respiratory bronchioles and alveoli, where oxygen diffuses into the bloodstream and carbon dioxide follows the opposite path to be removed from the body (see Figure 1.10).

INTERNAL RESPIRATION (GAS EXCHANGE IN THE TISSUES)

Internal respiration is the exchange of gases between blood and body tissues (see Figure 1.11). Oxygen is constantly used by cells to produce adenosine triphosphate (ATP), the main energy source for the body. This process also generates carbon dioxide as a waste product.

Since cells are always using oxygen, its concentration is lower in tissues than in the blood; this permits the movement of oxygen from the blood into the tissues. At the same time, CO_2 levels are higher in tissues than in blood, so it diffuses into the bloodstream to be carried

back to the lungs for removal. Once blood has released its oxygen, it is considered deoxygenated and returns to the heart to be pumped to the lungs for reoxygenation.

TRANSPORT OF GASES

The transport of oxygen and carbon dioxide is a vital function of the circulatory system, ensuring that body tissues receive the oxygen they need for energy production while also removing carbon dioxide, a waste product of metabolism. These gases travel through the bloodstream via two main components: plasma (the liquid part of blood) and haemoglobin, a protein found in red blood cells (erythrocytes).

OXYGEN TRANSPORT

Oxygen is carried in the blood in two ways:

1. Bound to haemoglobin (98%): The majority of oxygen is transported by haemoglobin, a specialised protein within erythrocytes. Each red blood cell contains approximately 280 million haemoglobin molecules, and each haemoglobin molecule can carry up to four oxygen molecules. This binding occurs in the lungs, where oxygen diffuses into the bloodstream and attaches to haemoglobin to form oxyhaemoglobin.
2. Dissolved in plasma (2%): A small percentage of oxygen is directly dissolved in the blood plasma. While this amount is minimal, it plays a crucial role in maintaining oxygen supply to the tissues.

Once oxygenated blood reaches the tissues, oxygen is released from haemoglobin due to differences in oxygen concentration between the blood and the tissues. Oxygen moves from high concentration in the blood to lower concentration in body cells, where it is used for energy production in a process called cellular respiration.

CARBON DIOXIDE TRANSPORT

Carbon dioxide is transported from body tissues to the lungs in three ways:

1. As bicarbonate ions (70%): The majority of carbon dioxide reacts with water in red blood cells to form carbonic acid (H_2CO_3), which quickly breaks down into bicarbonate ions (HCO_3^-) and hydrogen ions (H^+). The bicarbonate ions are transported in plasma to the lungs, where the reaction is reversed, allowing carbon dioxide to be exhaled.
2. Bound to haemoglobin (carbaminohaemoglobin) (20%): Some carbon dioxide attaches directly to haemoglobin, forming carbaminohaemoglobin. Unlike oxygen, carbon dioxide binds to a different part of the haemoglobin molecule and does not compete with oxygen for binding sites.
3. Dissolved in plasma (10%): A small percentage of carbon dioxide is carried in the blood as a dissolved gas in plasma.

The efficiency of oxygen and carbon dioxide transport is essential for maintaining normal physiological functions. Factors that can affect this process include:

- Anaemia: A reduced number of red blood cells or low haemoglobin levels can impair oxygen delivery to tissues.
- Lung diseases, such as COPD, pneumonia, asthma: These conditions can interfere with oxygen uptake and carbon dioxide removal, leading to breathing difficulties.
- Carbon monoxide poisoning: Carbon monoxide competes with oxygen for haemoglobin binding sites, reducing oxygen transport and leading to tissue hypoxia.

Understanding the transportation of gases can help to recognise how respiratory and circulatory disorders can impact oxygen delivery and carbon dioxide removal, guiding appropriate clinical interventions.

BLOOD SUPPLY TO THE LUNGS

The lungs receive blood from two separate circulatory pathways: the pulmonary circulation and the bronchial circulation, each serving a distinct function.

1. Pulmonary circulation (gas exchange region)
   - Deoxygenated blood from the body is transported to the lungs via the right and left pulmonary arteries.
   - These arteries branch into smaller capillaries, which surround the alveoli, where gas exchange occurs.
   - Oxygen enters the blood and carbon dioxide is removed, reoxygenating the blood.
   - The oxygenated blood is then transported back to the left side of the heart via the four pulmonary veins, where it is pumped into systemic circulation to supply the body's tissues.
2. Bronchial circulation (conduction region)
   - The bronchial arteries, which originate from the aorta, supply oxygenated blood to the tissues of the lungs, including the bronchi, bronchioles and other supporting structures.
   - Some bronchial arteries connect with pulmonary arteries, creating a small overlap between the two circulatory systems.
   - The majority of blood from the bronchial circulation is drained back to the heart through the pulmonary veins or bronchial veins.

This dual blood supply ensures that both the alveoli (for gas exchange) and the lung tissues (for nourishment and maintenance) receive the necessary oxygen and nutrients to function effectively. See Figure 1.12 for blood flow between the lungs, the heart and the body.

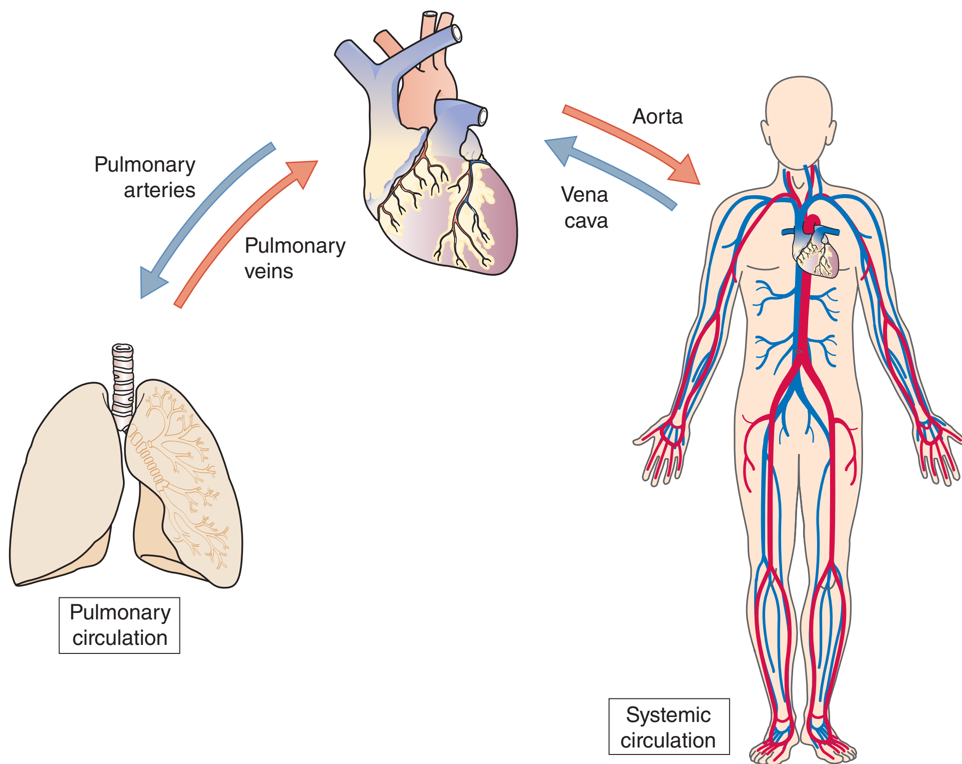

FIGURE 1.12 Blood flow between the lungs, the heart and the body. *Source*: Peate and Evans (2020). With permission of John Wiley & Sons.

CONCLUSION

This chapter has provided an overview of the anatomy and physiology of the respiratory system, which is divided into two main sections: the upper and lower respiratory tracts. The upper respiratory tract serves a critical protective function as it filters, warms and moistens the incoming air, helping to safeguard the more delicate structures of the lower respiratory tract. The lower respiratory tract, which includes the lungs and major airways, is responsible for gas exchange, oxygen is absorbed into the blood and carbon dioxide is expelled from the body.

Respiration itself involves four distinct physiological processes. The first is pulmonary ventilation, which refers to the act of breathing, moving air in and out of the lungs. The second is external respiration, the exchange of gases between the lungs and blood. These two processes are the primary functions of the respiratory system. The third process is the transport of gases, where oxygen and carbon dioxide are carried by the bloodstream throughout the body. Finally, internal respiration occurs, which is the exchange of gases between the blood and body tissues.

While the respiratory system is responsible for pulmonary ventilation and external respiration, it is important to note that the overall efficiency of respiration also relies heavily on a properly functioning cardiovascular system. This system ensures that oxygenated blood is circulated to the tissues, while carbon dioxide is carried back to the lungs for expulsion.

GLOSSARY OF TERMS

Alveoli: Tiny air sacs in the lungs where the exchange of oxygen and carbon dioxide occurs between the air and the blood.

Bronchi: The main passageways that conduct air into the lungs. The trachea divides into the right and left bronchi, which further divide into smaller bronchioles.

Bronchioles: Small branches of the bronchi that lead to the alveoli. They control airflow to the lungs and regulate the distribution of air.

Capillaries: Tiny blood vessels that surround the alveoli and facilitate gas exchange between the blood and the air in the alveoli.

Carbon dioxide (CO_2): A waste product of cellular metabolism that is transported in the blood and exhaled through the lungs.

Chemoreceptors: Sensory receptors that detect changes in the levels of gases (such as oxygen and carbon dioxide) in the blood and help regulate respiratory rate.

Diaphragm: A dome-shaped muscle located below the lungs that plays a key role in breathing by contracting and relaxing to allow lung expansion and exhalation.

Diffusion: The process by which gases such as oxygen and carbon dioxide move from areas of high concentration to areas of low concentration, allowing for gas exchange in the lungs and tissues.

Epiglottis: A flap of cartilage that covers the larynx during swallowing to prevent food or liquid from entering the airways.

External respiration: The process of gas exchange between the air in the alveoli and the blood in the pulmonary capillaries, where oxygen is absorbed and carbon dioxide is expelled.

Haemoglobin: A protein in red blood cells that binds to oxygen in the lungs and releases it in the tissues.

Internal respiration: The exchange of gases (oxygen and carbon dioxide) between the blood and body tissues.

Larynx: The voice box, located between the pharynx and trachea, responsible for sound production and protecting the airway during swallowing.

Lungs: A pair of cone-shaped organs located in the chest, where gas exchange occurs. The lungs contain alveoli for oxygen absorption and carbon dioxide removal.

Nasal cavity: The space inside the nose where air is filtered, warmed and moistened before entering the lungs.

Oxygen (O_2): A vital gas that is inhaled into the lungs, absorbed into the bloodstream and delivered to tissues for cellular metabolism.

Pharynx: The throat; a muscular passage that connects the nasal cavity and mouth to the larynx and oesophagus.

Pulmonary artery: The blood vessel that carries deoxygenated blood from the heart to the lungs for oxygenation.

Pulmonary vein: The blood vessel that returns oxygenated blood from the lungs to the heart.

Respiratory rate: The number of breaths taken per minute.

Trachea: The windpipe, a tube that conducts air from the larynx to the bronchi.

Ventilation: The process of moving air in and out of the lungs to enable gas exchange. It includes both inhalation and exhalation.

MULTIPLE CHOICE QUESTIONS

1. Which of the following is the main function of the respiratory system?
a) Circulating oxygen throughout the body
b) Removing waste products from the body
c) Facilitating gas exchange between oxygen and carbon dioxide
d) Producing white blood cells

2. Where does gas exchange between the lungs and the blood primarily occur?
a) Bronchi
b) Alveoli
c) Trachea
d) Pharynx

3. Which part of the respiratory system is responsible for filtering, warming and moistening the air we breathe?
a) Alveoli
b) Nasal cavity
c) Lungs
d) Diaphragm

4. What is the name of the muscle that plays a central role in the process of breathing?
a) Rectus abdominis
b) Trapezius
c) Diaphragm
d) Pectoralis major

5. The process of oxygen moving from the alveoli into the blood is an example of:
a) Active transport
b) Diffusion
c) Filtration
d) Endocytosis

6. What is the term for the process by which air is moved into and out of the lungs?
a) Respiration
b) Ventilation
c) Diffusion
d) Circulation

7. Which gas is primarily responsible for triggering the urge to breathe?
a) Nitrogen
b) Carbon dioxide
c) Oxygen
d) Carbon monoxide

8. Which of the following statements about the diaphragm is true?
a) It contracts during exhalation to push air out of the lungs.
b) It relaxes during inhalation to allow the lungs to expand.
c) It is controlled by the sympathetic nervous system.
d) It only functions during forced breathing.

9. Where are the central chemoreceptors located that detect carbon dioxide levels in the blood?
a) In the brainstem
b) In the carotid bodies
c) In the lungs
d) In the liver

10. Which of the following gases is mainly carried in the blood bound to haemoglobin?
a) Carbon dioxide
b) Oxygen
c) Nitrogen
d) Carbon monoxide

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