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Overview of the respiratory system

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INTRODUCTION TO RESPIRATORY MEDICINE

Understanding the respiratory system and the pathological processes that can affect it is a fundamental part of modern medicine. In the United Kingdom, approximately one in five people are diagnosed with asthma, chronic obstructive pulmonary disease (COPD) or another long-term respiratory condition during their lifetime. Unfortunately, a person dies from a respiratory disease every 5 minutes in the United Kingdom. Worldwide in 2015, four of the top ten causes of death were primary respiratory disorders (lower respiratory infections, COPD, lung cancers and tuberculosis), according to World Health Organization statistics.

There is significant morbidity associated with respiratory conditions, affecting millions of people across the world. In health, we hardly notice our breathing; however, when our breathing is compromised, we notice nothing else. In addition to morbidity, there are health economic consequences to respiratory disorders, with 8% of hospital admissions in the United Kingdom in 2011 due to respiratory disease. The implications of respiratory problems influence all medical and surgical specialities. An assessment of lung health is required before any surgery requiring general anaesthesia and informs the decision-making process prior to intensive care admission.

As a physician, understanding the respiratory system is vital in day-to-day practice. Having a firm grasp on normal physiology, control and response to insult is essential to recognizing, predicting and effectively managing illness. This book aims to outline the physiology, demonstrate how assessments are carried out and discuss the common conditions currently seen in respiratory medicine.

OVERALL STRUCTURE AND FUNCTION

Respiration

Respiration refers to the processes involved in oxygen transport from the atmosphere to the body tissues and the release and transportation of carbon dioxide produced in the tissues to the atmosphere.

Microorganisms rely on diffusion for the supply of oxygen to and removal of carbon dioxide from their environment. Humans, however, are unable to rely on diffusion because:

- Their surface area:volume ratio is too small.
- The diffusion distance from the surface of the body to the cells is too large and the process would be far too slow to be compatible with life.

Remember that diffusion time increases with the square of the distance, and, as a result, the human body has had to develop a specialized respiratory system to overcome this problem. This system has two components:

1. A gas-exchange system that provides a large surface area for the uptake of oxygen from, and the release of carbon dioxide to, the environment. This function is performed by the lungs.
2. A transport system that delivers oxygen to the tissues from the lungs and carbon dioxide to the lungs from the tissues. This function is carried out by the cardiovascular system.

Structure

The respiratory system can be neatly divided into upper respiratory tract (nasal and oral cavities, pharynx, larynx and trachea) and lower respiratory tract (main bronchi and lungs) (Fig. 1.1).

Upper respiratory tract

The upper respiratory tract has a large surface area and a rich blood supply, and its epithelium (respiratory epithelium) is covered by a mucus secretion. Within the nose, hairs are present, which act as a filter. The function of the upper respiratory tract is to warm, moisten and filter the air so that it is in a suitable condition for gaseous exchange in the distal part of the lower respiratory tract.

Lower respiratory tract

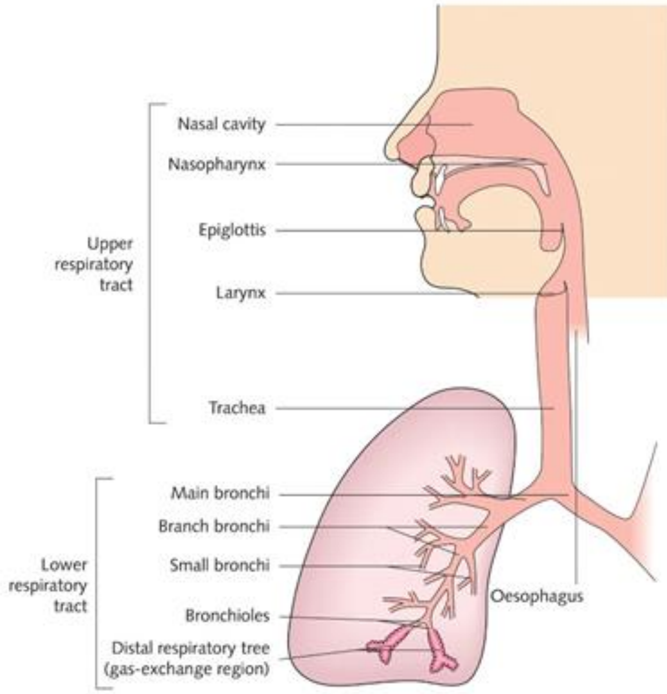
The lower respiratory tract consists of the lower part of the trachea, the two primary bronchi and the lungs. These structures are contained within the thoracic cavity.

Lungs

The lungs are the organs of gas exchange and act as both a conduit for air flow (the airway) and a surface for movement of oxygen into the blood and carbon dioxide out of the blood (the alveolar capillary membrane).

The lungs consist of airways, blood vessels, nerves and lymphatics, supported by parenchymal tissue. Inside the lungs, the two main bronchi divide into smaller and smaller airways until the end respiratory unit (acinus) is reached (Fig. 1.2).

Fig. 1.1 Schematic diagram of the respiratory tract.



Acinus

The acinus is the part of the airway involved in gaseous exchange (i.e., the passage of oxygen from the lungs to the blood and carbon dioxide from the blood to the lungs). It begins with the respiratory bronchioles and includes subsequent divisions of the airway and alveoli.

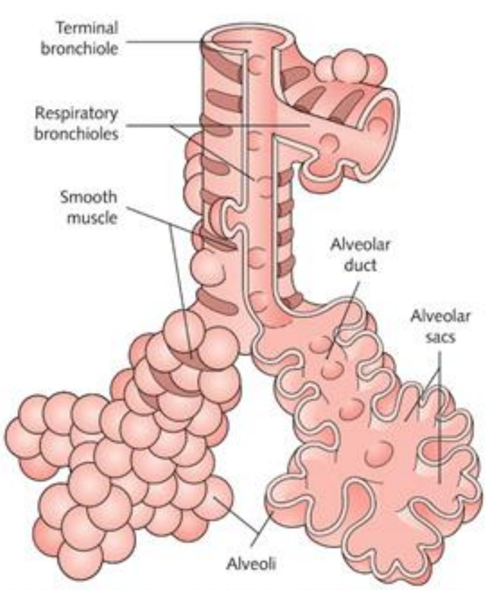


Fig. 1.2 The acinus, or respiratory unit. This part of the airway is involved in gas exchange.

Conducting airways

Conducting airways allow the transport of gases to and from the acinus but are themselves unable to partake in gas exchange. They include all divisions of the bronchi proximal to, but excluding, respiratory bronchioles.

Pleurae

The lung, chest wall and mediastinum are covered by two continuous layers of epithelium known as the pleurae. The visceral pleura is the inner pleura covering the lung and the parietal pleura is the outer pleura covering the chest wall and mediastinum. These two pleurae are closely opposed and are separated by only a thin layer of liquid. The liquid acts as a lubricant and allows the two surfaces to slip over each other during breathing.

BASIC CONCEPTS IN RESPIRATION

The supply of oxygen to body tissues is essential for life; after only a brief period without oxygen, cells undergo irreversible change and eventually die. The respiratory system plays an essential role in preventing tissue hypoxia by optimizing

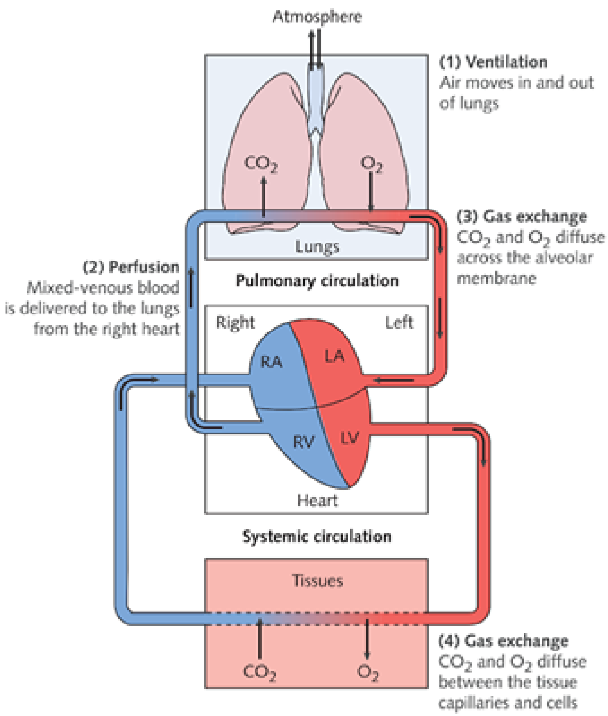


Fig. 1.3 Key steps in respiration. *RA,* Right atrium; *LA,* left atrium; *RV,* right ventricle; *LV,* left ventricle.

the oxygen content of arterial blood through efficient gas exchange. The three key steps involved in gas exchange are:

1. Ventilation.
2. Perfusion.
3. Diffusion.

Together these processes ensure that oxygen is available for transport to the body tissues and that carbon dioxide is eliminated (Fig. 1.3). If any of the three steps are compromised, e.g., through lung disease, then the oxygen content of the blood will fall below normal (hypoxaemia) and levels of carbon dioxide may rise (hypercapnia) (Table 1.1). In clinical practice, we do not directly test for tissue hypoxia but look for:

- Symptoms and signs of impaired gas exchange (e.g., breathlessness or central cyanosis).
- Abnormal results from arterial blood gas tests.

Table 1.1 Common respiratory terms

Term	Definition
Hypocapnia	Decreased carbon dioxide tension in arterial blood (P_aCO_2 <4.8 kPa or 35 mmHg)
Hypercapnia	Increased carbon dioxide tension in arterial blood (P_aCO_2 >6 kPa or 45 mmHg)
Hypoxaemia	Deficient oxygenation of the arterial blood
Hypoxia	Deficient oxygenation of the tissues
Hyperventilation	Ventilation that is in excess of metabolic requirements (results in hypocapnia)
Hypoventilation	Ventilation that is too low for metabolic requirements (results in hypercapnia)

Ventilation

Ventilation is the movement of air in and out of the respiratory system. It is determined by both:

- The respiratory rate (i.e., number of breaths per minute, normally 12–20).
- The volume of each breath, also known as the tidal volume.

A change in ventilation in response to the metabolic needs of the body, can therefore be brought about by either:

- Altering the number of breaths per minute, or
- Adjusting the amount of air that enters the lungs with each breath.

In practice, the most common response to hypoxaemia is rapid, shallow breathing, which increases the elimination of carbon dioxide and often leads to hypocapnia. However, it should be noted that a raised respiratory rate, or tachypnoea, is not the same as hyperventilation. The term hyperventilation refers to a situation where ventilation is too great for the body's metabolic needs.

The mechanisms of ventilation

The movement of air into and out of the lungs takes place because of pressure differences caused by changes in lung volumes. Air flows from a high-pressure area to a low-pressure area. We cannot change the local atmospheric pressure around us to a level higher than that inside our lungs; the only obvious alternative is to lower the pressure within the lungs. We achieve this pressure reduction by expanding the size of the chest.

The main muscle of inspiration is the diaphragm, upon which the two lungs sit. The diaphragm is dome shaped; contraction flattens the dome, increasing intrathoracic volume. This is aided by the external intercostal muscles, which raise the ribcage; this results in a lowered pressure within the thoracic cavity and hence the lungs, supplying the driving force for air flow into the lungs. Inspiration is responsible for most of the work of breathing; diseases of the lungs or chest wall may increase the workload so that accessory muscles are also required to maintain adequate ventilation.

Expiration is largely passive, being a result of elastic recoil of the lung tissue. However, in forced expiration (e.g., during coughing), the abdominal muscles increase intraabdominal pressure, forcing the contents of the abdomen against the diaphragm. In addition, the internal intercostal muscles lower the ribcage. These actions greatly increase intrathoracic pressure and enhance expiration.

Impaired ventilation

There are two main types of disorder that impair ventilation. These are:

1. Obstructive disorders:
   - Airways are narrowed and resistance to air flow is increased.
   - Mechanisms of airway narrowing include inflamed and thickened bronchial walls (e.g., asthma), airways filled with mucus (e.g., chronic bronchitis, asthma) and airway collapse (e.g., emphysema).
2. Restrictive disorders:
   - Lungs are less able to expand and so the volume of gas exchanged is reduced.
   - Mechanisms include stiffening of lung tissue (e.g., pulmonary fibrosis) or inadequacy of respiratory muscles (e.g., Duchenne muscular dystrophy).

Obstructive and restrictive disorders have characteristic patterns of lung function, measured by pulmonary function tests.

Ventilatory failure occurs if the work of breathing becomes excessive and muscles fail. In this situation, or to prevent it from occurring, mechanical ventilation is required.

Perfusion

The walls of the alveoli contain a dense network of capillaries bringing mixed-venous blood from the right heart. The barrier separating blood in the capillaries and air in the alveoli is extremely thin. Perfusion of blood through these pulmonary capillaries allows diffusion, and therefore gas exchange, to take place.

Ventilation:perfusion inequality

To achieve efficient gaseous exchange, it is essential that the flow of gas (ventilation: *V*) and the flow of blood (perfusion: *Q*) are closely matched. The *V/Q* ratio in a normal, healthy lung is approximately one. Two extreme scenarios illustrate mismatching of ventilation and perfusion (Fig. 1.4). These are:

- Normal alveolar ventilation but no perfusion (e.g., owing to a blood clot obstructing flow).
- Normal perfusion but no air reaching the lung unit (e.g., owing to a mucus plug occluding an airway).

V/Q inequality is the most common cause of hypoxaemia and underlies many respiratory diseases.

Diffusion

At the gas-exchange surface, diffusion occurs across the alveolar capillary membrane. Molecules of carbon dioxide and oxygen diffuse along their partial pressure gradients.

Partial pressures

Air in the atmosphere, before it is inhaled and moistened, contains 21% oxygen. This means that:

- 21% of the total molecules in air are oxygen molecules.
- Oxygen is responsible for 21% of the total air pressure; this is its partial pressure, measured in mmHg or kPa and abbreviated as PO_2 (Table 1.2).

Partial pressure also determines the gas content of liquids, but it is not the only factor. Gas enters the liquid as a solution, and the amount that enters depends on its solubility.

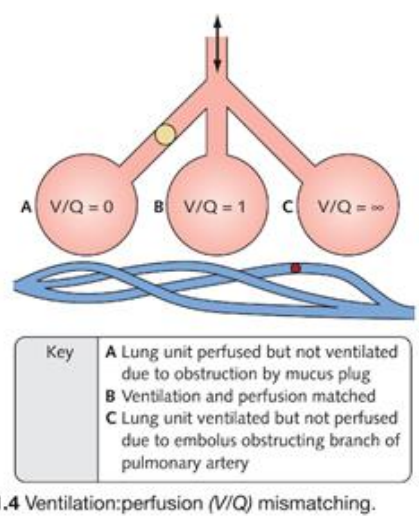


Fig. 1.4 Ventilation:perfusion *(V/Q)* mismatching.

Table 1.2 Abbreviations used in denoting partial pressures[a]

Abbreviation	Definition
PO_2	Oxygen tension in blood (either arterial or venous)
P_aO_2	Arterial oxygen tension
P_vO_2	Oxygen tension in mixed-venous blood
P_AO_2	Alveolar oxygen tension

[a] *Carbon dioxide tensions follow the same format. (PCO_2, etc.)*

The more soluble a gas, the more molecules will enter solution for a given partial pressure. The partial pressure of a gas in a liquid is sometimes referred to as its tension (i.e., arterial oxygen tension is the same as P_aO_2).

As blood perfusing the pulmonary capillaries is mixed-venous blood:

- Oxygen will diffuse from the higher PO_2 environment of the alveoli into the capillaries.
- Carbon dioxide will diffuse from the blood towards the alveoli, where PCO_2 is lower.

Blood and gas equilibrate as the partial pressures become the same in each and gas exchange then stops.

Oxygen transport

Once oxygen has diffused into the capillaries, it must be transported to the body tissues. The solubility of oxygen in the blood is low and only a small percentage of the body's requirement can be carried in dissolved form. Therefore, most of the oxygen is combined with haemoglobin in red blood cells. Haemoglobin has four binding sites and the amount of oxygen carried by haemoglobin in the blood depends on how many of these sites are occupied. If they are all occupied by oxygen, the molecule is said to be saturated. The oxygen saturation (S_aO_2) tells us the relative percentage of the maximum possible sites that can be bound. Note that anaemia will not reduce S_aO_2; lower haemoglobin means there are fewer available sites but the relative percentage of possible sites that are saturated stays the same.

The relationship between the partial pressure of oxygen and percentage saturation of haemoglobin is represented by the oxygen dissociation curve.

Diffusion defects

If the blood–gas barrier becomes thickened through disease, then the diffusion of oxygen and carbon dioxide will be impaired. Any impairment is particularly noticeable during exercise, when pulmonary flow increases and blood spends an even shorter time in the capillaries, exposed to alveolar oxygen. Impaired diffusion is, however, a much less common cause of hypoxaemia than V:Q mismatching.

CONTROL OF RESPIRATION

Respiration must respond to the metabolic demands of the body. This is achieved by a control system within the brainstem that receives information from various sources in the body where sensors monitor:

- Partial pressures of oxygen and carbon dioxide in the blood.
- pH of the extracellular fluid within the brain.
- Mechanical changes in the chest wall.

Based on the information they receive, the respiratory centres modify ventilation to ensure that oxygen supply and carbon dioxide removal from the tissues match their metabolic requirements. The actual mechanical change to ventilation is carried out by the respiratory muscles: these are known as the effectors of the control system.

COMMON PITFALLS

It is easy to get confused about P_aO_2, S_aO_2 and oxygen content. P_aO_2 tells us the pressure of the oxygen molecules dissolved in plasma, not those bound to haemoglobin. It is not a measure of how much oxygen is in the arterial blood. S_aO_2 tells us how many of the possible haemoglobin binding sites are occupied by oxygen. To calculate the amount of oxygen you would also need to know haemoglobin levels and how much oxygen is dissolved. Oxygen content (C_aO_2) is the only value that actually tells us how much oxygen is in the blood and, unlike P_aO_2 or S_aO_2, it is given in units that denote quantity (mL O_2/dL).

Respiration can also be modified by higher centres (e.g., during speech, anxiety, emotion).

OTHER FUNCTIONS OF THE RESPIRATORY SYSTEM

Respiration is also concerned with a number of other functions, including metabolism, excretion, hormonal activity and, most importantly:

- The pH of body fluids.
- Regulation of body temperature.

Acid–base regulation

Carbon dioxide forms carbonic acid in the blood, which dissociates to form hydrogen ions, lowering pH. By controlling the partial pressure of carbon dioxide, the respiratory