1 Structure of the respiratory system: lungs, airways and dead space

Figure 1a Lung lobes

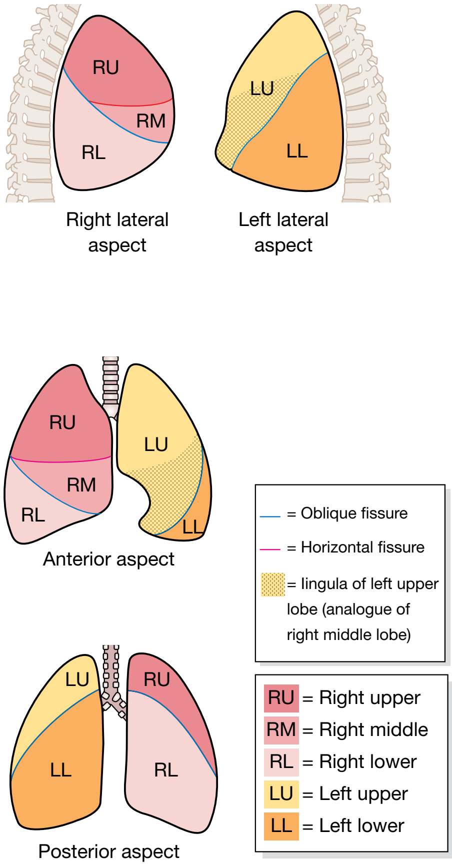


Figure 1b The airways

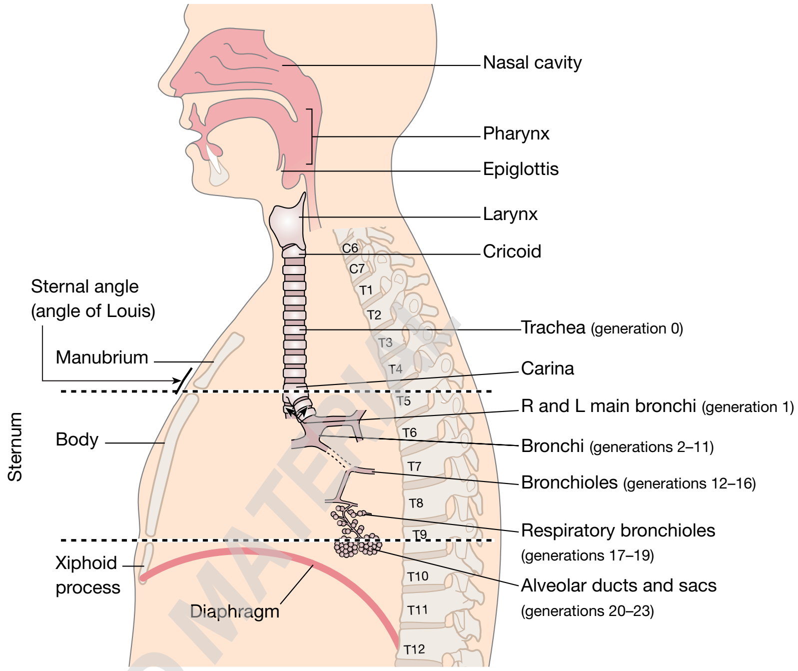
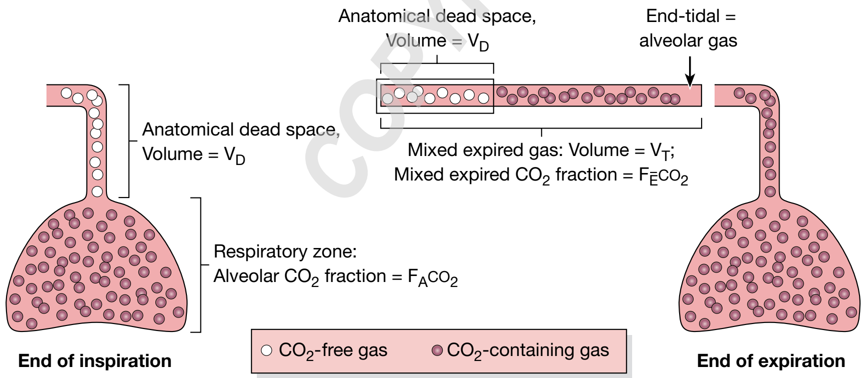


Figure 1c Bohr equation for measuring dead space



In an expired breath none of the CO_2 expired comes from the dead space region

∴ Quantity of CO_2 in mixed expired air = quantity of CO_2 from alveolar region

$$V_T \times F_{\bar{E}}CO_2 = (V_T - V_D) \times F_ACO_2$$

$$\therefore V_D = V_T\,(F_ACO_2 - F_{\bar{E}}CO_2)/\,F_ACO_2$$

The Respiratory System at a Glance, Fifth Edition. Jeremy P.T. Ward, Jane Ward, and Richard M. Leach.
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Lungs and pleura

The respiratory system consists of a pair of **lungs** within the **thoracic cage** (Chapter 2). Its main function is gas exchange; other roles include speech, filtration of microthrombi arriving from systemic veins and metabolic activities such as conversion of angiotensin I to angiotensin II and removal or deactivation of serotonin, bradykinin, norepinephrine, acetylcholine and drugs such as propranolol and chlorpromazine. The **right lung** is divided by **transverse** and **oblique fissures** into three lobes: upper, middle and lower. The **left lung** has an **oblique fissure** and consists of two lobes; the inferior/anterior part of the left upper lobe, the lingula, is analogous to the middle lobe of the right lung (Figure 1a). Vessels, nerves and lymphatics enter the lungs on their medial surfaces at the lung root or **hilum**. Each lobe is divided into wedge-shaped **bronchopulmonary segments** with their apices at the hilum and bases at the lung surface. Each bronchopulmonary segment is supplied by its own segmental bronchus, artery and vein and can be removed surgically with little bleeding or air leakage from the remaining lung.

The **pulmonary nerve plexus** lies behind each hilum, receiving fibres from both **vagi** and the second to fourth thoracic **ganglia** of the **sympathetic trunk**. Each vagus contains sensory afferents from lungs and airways, parasympathetic bronchoconstrictor and secretomotor efferents, and non-adrenergic, non-cholinergic (NANC) nerves. Sympathetic noradrenergic fibres supplying airway smooth muscle are sparse in humans, and the β_2-adrenergic receptors are stimulated by circulating catecholamines from the adrenal glands (Chapter 7).

Each lung is lined by a thin membrane, the **visceral pleura**, which is continuous with the **parietal pleura** lining the chest wall, diaphragm, pericardium and mediastinum. The space between the parietal and visceral layers is tiny in health and lubricated with pleural fluid. The right and left pleural cavities are separate and each extends as the **costodiaphragmatic recess** below the lungs even during full inspiration. The parietal pleura is segmentally innervated by **intercostal nerves** and by the **phrenic nerve (C3, 4, 5)**; pain from pleural inflammation (**pleurisy**) is often referred to the chest wall or shoulder tip. The visceral pleura lacks sensory innervation.

Lymph channels are absent in alveolar walls; they accompany small blood vessels conveying lymph towards the **hilar bronchopulmonary nodes** and from there to **tracheobronchial nodes** at the tracheal bifurcation. Some lymph from the lower lobe drains to the **posterior mediastinal nodes**.

The **upper respiratory tract** consists of the nose, pharynx and larynx. The **lower respiratory tract** (Figure 1b) starts with the trachea at the lower border of the **cricoid cartilage**. It bifurcates into **right** and **left main bronchi** at the level of the **sternal angle** and T4/5 (lower when upright and in inspiration). The right main bronchus is wider, shorter and more vertical than the left, so inhaled foreign bodies enter it more easily.

Airways

The airways divide repeatedly, with each successive **generation** approximately doubling in number. The **trachea** and **main bronchi** have U-shaped cartilage linked posteriorly by smooth muscle. Lobar bronchi supply the three right and two left lung lobes and divide to give **segmental bronchi** (generations 3 and 4). The total cross-sectional area of each generation is minimum here, after which it rises rapidly, as increased numbers more than make up for their reduced size. Generations 5–11 are small bronchi, the smallest being 1 mm in diameter. The lobar, segmental and small bronchi are supported by irregular plates of cartilage, with bronchial smooth muscle forming helical bands. **Bronchioles** start at about generation 12 and from this point onwards cartilage is absent. These airways are embedded in lung tissue, which holds them open like tent guy ropes. The **terminal bronchioles** (generation 16) lead to **respiratory bronchioles**, the first generations to have alveoli (Chapter 5) in their walls. These lead to **alveolar ducts** and **alveolar sacs** (generation 23), whose walls are entirely composed of **alveoli**.

The bronchi and airways down to the terminal bronchioles receive nutrition from the **bronchial arteries** arising from the descending aorta. The respiratory bronchioles, alveolar ducts and sacs are supplied by the **pulmonary circulation** (Chapter 14).

The airways from trachea to respiratory bronchioles are lined with **ciliated columnar or cuboidal epithelial cells**. **Goblet cells** and **submucosal glands** in the conducting airways secrete **mucus.** Synchronous beating of cilia moves the mucus and associated debris to the mouth (**mucociliary clearance**; Chapter 19). In the respiratory bronchioles, club cells secrete the fluid and substances involved in small airway protection; as stem cells they can divide to repair damaged epithelium. Epithelial cells forming the walls of alveoli and alveolar ducts are unciliated, and largely very thin **type I alveolar pneumocytes**. These form the gas exchange surface with the capillary endothelium (**alveolar–capillary membrane**). The less common **type II pneumocytes** are mostly found at the junction between alveoli. They are stem cells, which can divide following lung damage. They secrete **surfactant**, which reduces surface tension and has a role in lung immunity (Chapters 6 and 19).

Dead space

The upper respiratory tract and airways as far as the terminal bronchioles do not take part in gas exchange. These **conducting airways** form the **anatomical dead space** whose volume (V_D) is normally about 150 ml. These airways have an air-conditioning function, warming, filtering and humidifying inspired air.

Alveoli that have lost their blood supply (e.g. because of a **pulmonary embolus**) no longer take part in gas exchange and form **alveolar dead space**. The sum of the anatomical and alveolar dead space is known as the **physiological dead space**. In health, all alveoli take part in gas exchange, so physiological dead space normally equals anatomical dead space.

The volume of a breath or **tidal volume** (V_T) is about 500 ml at rest. Resting **respiratory frequency** (f) is about 15 breaths/minute, so the volume entering the lungs each minute, the **minute ventilation** ($\dot{V}$), is about 7500 ml/minute (500 × 15) at rest. **Alveolar ventilation** ($\dot{V}_A$) is the volume taking part in gas exchange each minute. At rest, with a dead-space volume of 150 ml, alveolar ventilation is about 5250 ml/minute ([500 − 150] × 15).

The **Bohr method** for measuring anatomical dead space uses the principle that the degree to which dead-space gas (0% CO_2) dilutes alveolar gas (~5% CO_2) to give mixed expired gas (~3.5% CO_2) depends on its volume (Figure 1c). **Alveolar CO_2 fraction**, F_ACO_2, is measured from an end-expiratory (**end-tidal**) gas sample. The Bohr equation can be modified to measure physiological dead space by using arterial $P\text{CO}_2$ to estimate the CO_2 in the gas-exchanging or **ideal alveoli**.