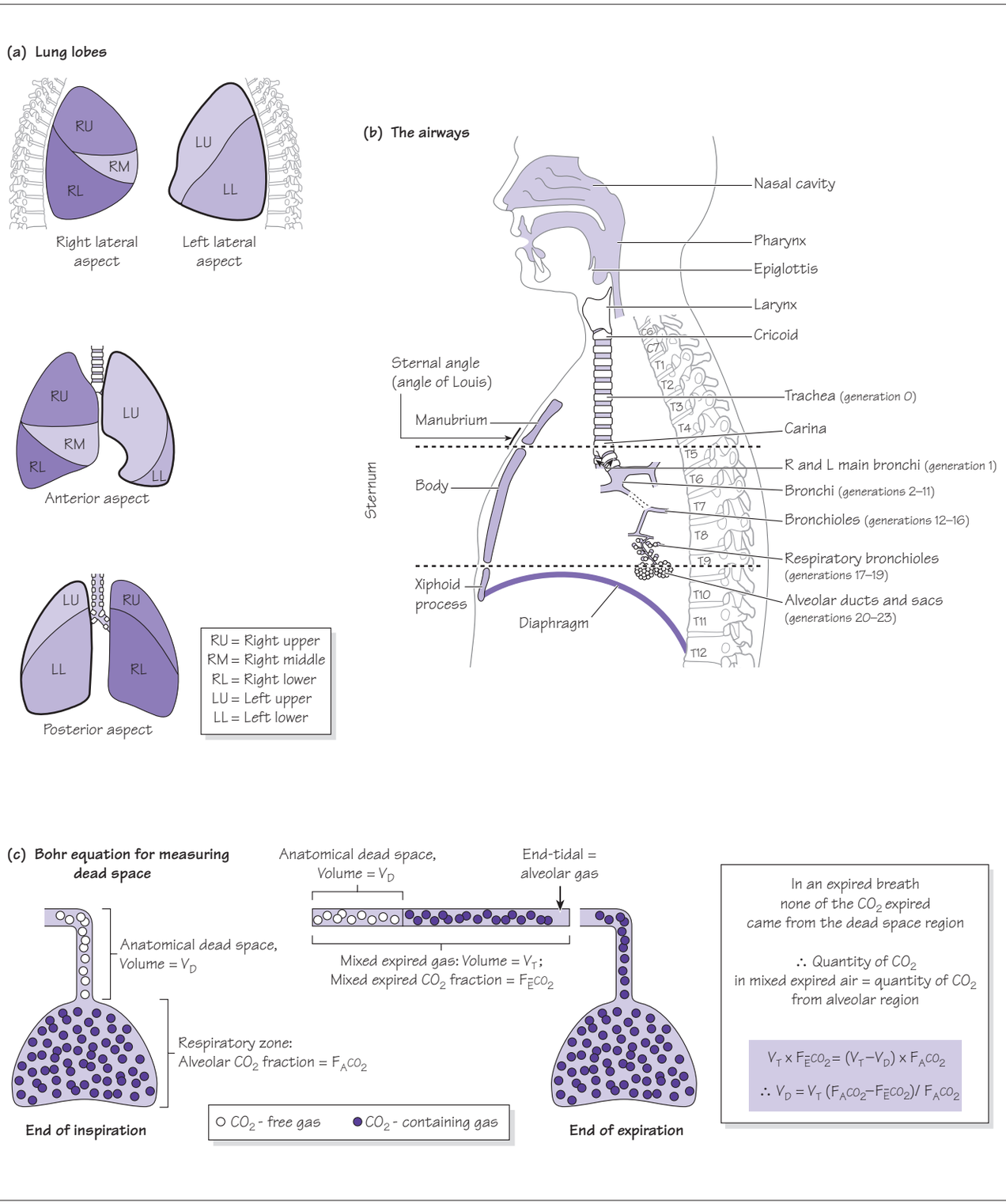
1 Structure of the respiratory system: lungs, airways and dead space



Lungs

The respiratory system consists of a pair of **lungs** within the **thoracic cage** (Chapter 2). Its main function is gas exchange, but 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 two lobes (Fig. 1a). Vessels, nerves and lymphatics enter the lungs on their medial surfaces at the lung root or **hilum**. Each lobe is divided into a number of 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 and parasympathetic bronchoconstrictor and secretomotor efferents. Sympathetic fibres are bronchodilator but relatively sparse.

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**, and so 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, but 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** (Fig. 1b) starts with the trachea at the lower border of the **cricoid cartilage**, level with the sixth cervical vertebra (C6). 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 on 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 generation 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 13).

The airways from trachea to respiratory bronchioles are lined with **ciliated columnar epithelial cells**. **Goblet cells** and **submucosal glands** secrete **mucus**. Synchronous beating of cilia moves the mucus and associated debris to the mouth (**mucociliary clearance**) (Chapter 18). Epithelial cells forming the walls of alveoli and alveolar ducts are unciliated, and largely very thin **type I alveolar pneumocytes** (alveolar cells; *squamous epithelium*). These form the gas exchange surface with the capillary endothelium (**alveolar-capillary membrane**). A few **type II pneumocytes** secrete **surfactant** which reduces surface tension and prevents alveolar collapse (Chapters 6 & 18).

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** (V_D), whose volume 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—for example 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**, ventilation of which is wasted in terms of gas exchange. In health, all alveoli take part in gas exchange, so physiological dead space 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/min, so the volume entering the lungs each minute, the **minute ventilation** ($\dot{V}$) is about 7500 mL/min (=500 × 15) at rest. **Alveolar ventilation** ($\dot{V}_A$) is the volume taking part in gas exchange each minute. At rest, dead space volume = 150 mL and alveolar ventilation is 5250 mL/min (=(500–150) × 15).

The **Bohr method** for measuring anatomical dead space is based on the principle that the degree to which dead space gas (0% CO_2) dilutes alveolar gas (about 5% CO_2) to give mixed expired gas (about 3.5%) depends on its volume (Fig. 1c). **Alveolar gas** can be sampled at the end of the breath as **end-tidal gas**. The Bohr equation can be modified to measure physiological dead space by using arterial P_{CO_2} to estimate the CO_2 in the gas-exchanging or **ideal alveoli**.