Blood Vessels

The pulmonary artery arises from the right ventricle and branches until it terminates in a meshwork of capillaries that surround the alveoli. This creates a large surface area that facilitates gas exchange. Blood returns to the heart through pulmonary veins that course through the lungs, coalesce into four main pulmonary veins, and empty into the left atrium. The pulmonary circulation is a low-resistance circuit; pulmonary vascular resistance is about one tenth of the resistance in the systemic circulation. Pulmonary vessels can be easily recruited to accommodate increases in blood flow while maintaining low pressure and resistance. Accordingly, during exercise, any increase in cardiac output can be distributed through the lung without significantly increasing pulmonary arterial pressures.

A separate vascular system, the bronchial system, also supplies the lung. The bronchial arteries originate from the aorta and, in contrast to the pulmonary arteries, are under systemic pressure. These vessels provide nutrients to lung structures proximal to the alveoli. Two thirds of the bronchial circulation drains into the pulmonary veins and then empties into the left atrium. This blood, which has low oxygen content, mixes with the freshly oxygenated blood from the pulmonary veins to lower the oxygen content of the blood that enters the systemic circulation.

PHYSIOLOGY

Ventilation

Ventilation refers to the bulk transport of air from the atmosphere to the alveolus. The product of tidal volume (VT) and breathing frequency (f) represents the total volume of air delivered to the lung per minute (minute ventilation). However, not all air entering the lung is in contact with gas-exchanging units. The portion of VT that fills the respiratory zone and alveoli and is available for gas exchange constitutes the alveolar volume (VA), whereas the portion remaining in the conducting airways is the anatomic dead space volume (VD) (Fig. 15-4). The ratio of VD to VT is called the *dead space ratio* (VD/VT). Normally, one third of a breath is dead space (VD/VT = ⅓). The amount of fresh air reaching the alveoli is VA − VD. With large breaths, the dead space becomes a smaller fraction of the total tidal volume. Therefore, for a given VT, slow, deep breathing results in greater VA and improved gas exchange compared with rapid, shallow breathing.

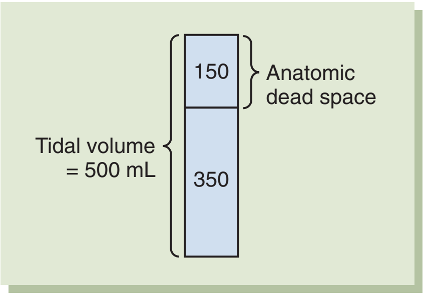

FIGURE 15-4 Schematic diagram of the inspired volume of air that participates in gas exchange (VA, 350 mL) and the volume of anatomic dead space (VD, 150 mL), which together provide a tidal breath (VT) of 500 mL.

The VD/VT ratio can be calculated by the Bohr method, as follows:

$$\mathrm{VD/VT} = (\mathrm{Pa}_{\mathrm{CO}_2} - \mathrm{PE}_{\mathrm{CO}_2})/\mathrm{Pa}_{\mathrm{CO}_2}$$

where $\mathrm{Pa}_{\mathrm{CO}_2}$ is the arterial partial pressure of carbon dioxide and $\mathrm{PE}_{\mathrm{CO}_2}$ is the partial pressure of carbon dioxide in mixed expired gas (i.e., the mixture of CO_2-rich gas that enters the alveoli from the pulmonary capillaries and dead space gas, which is devoid of CO_2). $\mathrm{PE}_{\mathrm{CO}_2}$ increases during expiration, reaching a plateau at end-expiration. At end-expiration, the $\mathrm{PE}_{\mathrm{CO}_2}$ represents exhaled alveolar gas that has been in equilibrium with pulmonary capillary blood. In healthy individuals, the $\mathrm{PE}_{\mathrm{CO}_2}$ at end-expiration is equivalent to the $\mathrm{Pa}_{\mathrm{CO}_2}$.

Ventilation of the dead space is wasted ventilation, because only V_A participates in gas exchange. Therefore, as the metabolic rate and carbon dioxide production increase, VA must increase to maintain an arterial $\mathrm{P}_{\mathrm{CO}_2}$ of 40 mm Hg. The relationship among these variables is described by the alveolar carbon dioxide equation:

$$\mathrm{PA}_{\mathrm{CO}_2} = \mathrm{CO}_2 \text{ production}/\dot{\mathrm{V}}\mathrm{A}$$

where $\mathrm{PA}_{\mathrm{CO}_2}$ is the partial pressure of carbon dioxide in the alveolus and $\dot{V}_A$ is alveolar ventilation. From this equation, one appreciates that the partial pressure of carbon dioxide in the alveolus is inversely proportional to alveolar ventilation.

The relationship described by the alveolar oxygen equation is similar:

$$\mathrm{PA}_{\mathrm{O}_2} = \mathrm{O}_2 \text{ consumption}/\dot{\mathrm{V}}\mathrm{A}$$

However, this relationship is more complicated because $\mathrm{PA}_{\mathrm{O}_2}$ also is proportional to the fraction of inspired oxygen, the water vapor pressure, and the partial pressure of carbon dioxide in the alveolus (discussed later). The implications of the alveolar carbon dioxide and oxygen relationships are that (1) maintenance of a constant alveolar gas composition depends on a constant ratio of ventilation to metabolic rate; (2) if ventilation is too high (hyperventilation), alveolar $\mathrm{P}_{\mathrm{CO}_2}$ will be low and alveolar $\mathrm{P}_{\mathrm{O}_2}$ will be high; and (3) if ventilation is too low (hypoventilation), alveolar $\mathrm{P}_{\mathrm{CO}_2}$ will be high and alveolar $\mathrm{P}_{\mathrm{O}_2}$ will be low.

Mechanics of Breathing

Respiratory mechanics is the study of forces needed to deliver air to the lung and how these forces govern the volume and flow of gases. Mechanically, the respiratory system consists of two structures: the lungs and the chest wall. The lungs are elastic (spring-like) structures that are situated within another elastic structure, the chest wall. At end-expiration, with absent respiratory muscle activity, the inward recoil of the lung is exactly balanced by the outward recoil of the chest wall, representing the equilibrium position of the lung–chest wall unit. Normally, the recoil of the lung is always inward (favoring lung deflation), and the recoil of the chest wall is outward (favoring inflation); at high lung volumes, however, the chest wall also recoils inward (Fig. 15-5). The energy required to stretch the respiratory system beyond its equilibrium state (end-expiration during quiet breathing) is provided by the inspiratory muscles. With normal quiet breathing, gas flow out of the lung is usually accomplished by passive recoil of the respiratory system.