The Respiratory System

INTRODUCTION

The primary function of respiration is to obtain O_2 for use by the body's cells and to eliminate the CO_2 the cells produce.

Steps of respiration

Respiration encompasses two separate but related processes: internal respiration and external respiration.

INTERNAL AND EXTERNAL RESPIRATION

The term internal or cellular respiration refers to the intracellular metabolic processes carried out within the mitochondria, which use O_2 and produce CO_2 while deriving energy from nutrient molecules. The term external respiration refers to the entire sequence of events in the exchange of O_2 and CO_2 between the external environment and the cells of the body. External respiration encompasses four steps (Figure 12-1):

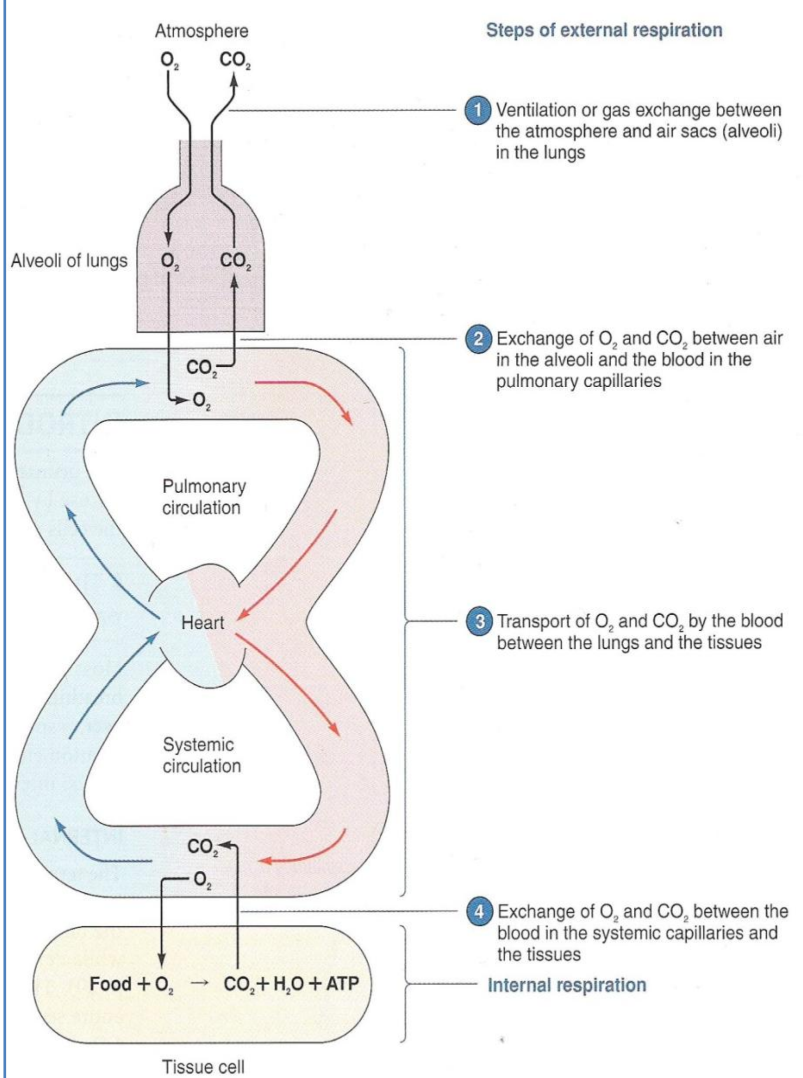


FIGURE 12-1

External and internal respiration. External respiration encompasses the steps involved in the exchange of O_2 and CO_2 between the external environment and tissue cells (steps 1 through 4). Internal respiration encompasses the intracellular metabolic reactions involving the use of O_2 to derive energy (ATP) from food, producing CO_2 as a by-product.

1. Air is alternately moved in and out of the lungs so that air can be exchanged between the atmosphere (external environment) and air sacs *(alveoli)* of the lungs. This exchange is accomplished by the mechanical act of breathing, or ventilation. The rate of ventilation is regulated to adjust the flow of air between the atmosphere and alveoli according to the body's metabolic needs for O_2 uptake and CO_2 removal.

2. Oxygen and CO_2 are exchanged between air in the alveoli and blood within the pulmonary *(pulmonary* means "lung") capillaries by the process of diffusion.

3. The blood transports O_2 and CO_2 between the lungs and tissues.

4. Oxygen and CO_2 are exchanged between the tissues and blood by the process of diffusion across the systemic (tissue) capillaries.

The respiratory system does not accomplish all the steps of respiration; it is involved only with ventilation and the exchange of O_2 and CO_2 between the lungs and blood (steps I and 2). The circulatory system carries out the remaining steps.

NONRESPIRATORY FUNCTIONS OF THE RESPIRATORY SYSTEM

The respiratory system also fills these nonrespiratory functions:

- It provides a route for water loss and heat elimination.
- It enhances venous return (see the "respiratory pump".
- It helps maintain normal acid-base balance by altering the amount of H^+ -generating CO_2 exhaled
- It enables speech, singing, and other vocalization.
- It defends against inhaled foreign matter
- It removes, modifies, activates, or inactivates various materials passing through the pulmonary circulation
- The nose, a part of the respiratory system, serves as the organ of smell

The respiratory airways

The respiratory system includes the respiratory airways leading into the lungs. The respiratory airways are tubes that carry air between the atmosphere and air sacs, the latter being the only site where gases can be exchanged between air and blood. The airways begin with the nasal passages (nose) (Figure I2-2a). The nasal passages open into the pharynx (throat), which serves as a common passageway for both the respiratory and digestive systems. Two tubes lead from the pharynx-the trachea (windpipe), through which air is conducted to the lungs, and the esophagus, the tube through which food passes to the stomach. Air normally enters the pharynx through the nose, but it can enter by the mouth as well when the nasal passages are congested; Because the pharynx serves as a common passageway for food and air, reflex mechanisms close off the trachea during swallowing so that food enters the esophagus and not the airways. The esophagus stays closed except during swallowing to keep air from entering the stomach during breathing.

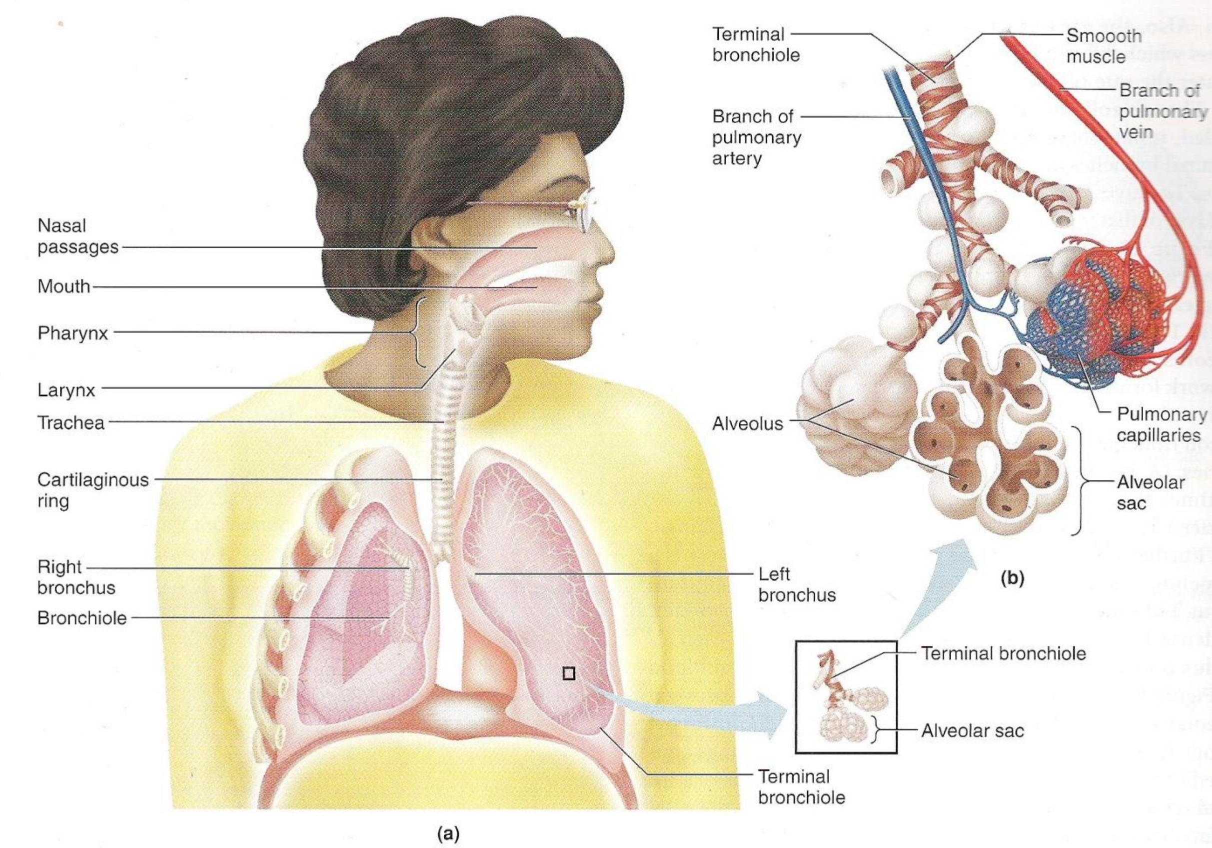


FIGURE 12-2

Anatomy of the respiratory system. (a) The respiratory airways. (b) Enlargement of the alveoli (air sacs) at the terminal end of the airways. Most alveoli are clustered in grapelike arrangements at the end of the terminal bronchioles.

The larynx, or voice box, is located at the entrance of the trachea. The anterior protrusion of the larynx forms the "Adam's apple." The vocal folds, two bands of elastic tissue that lie across the opening of the larynx, can be stretched and positioned in different shapes by laryngeal muscles. As air is moved past the taut vocal folds, they vibrate to produce the many different sounds of speech. The lips, tongue, and soft palate modify the sounds into recognizable sound patterns. During swallowing, the vocal folds assume a function not related to speech; they are brought into tight apposition to each other to close off the entrance to the trachea.

Beyond the larynx, the trachea divides into two main branches, the right and left bronchi, which enter the right and left lungs, respectively. Within each lung, the bronchus continues to branch into progressively narrower, shorter, and more numerous airways, much like the branching of a tree. The smaller branches are known as bronchioles. Clustered at the ends of the terminal bronchioles are the alveoli, the tiny air sacs where gases are exchanged between air and blood (Figure 12-2b).

The gas-exchanging alveoli

The lungs are ideally structured for gas exchange. According to Fick's law of diffusion, the shorter the distance through which diffusion must take place, the greater the rate of diffusion. Also, the greater the surface area across which diffusion can take place, the greater the rate of diffusion.

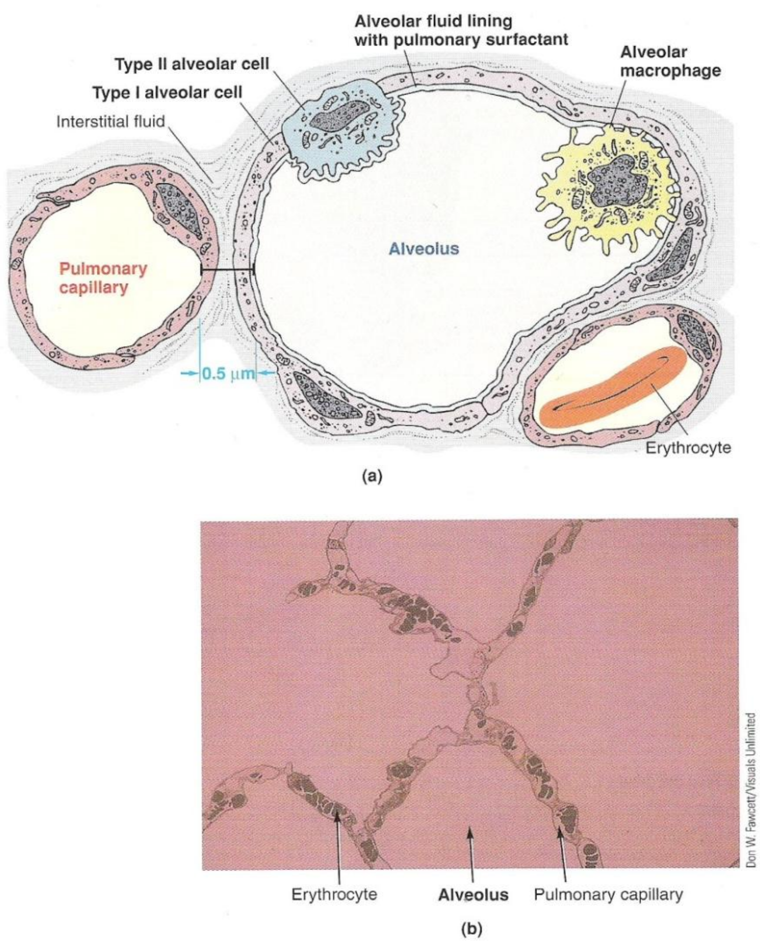


FIGURE 12-3

Alveolus and associated pulmonary capillaries. (a) A schematic representation of a detailed electron microscope view of an alveolus and surrounding capillaries. A single layer of flattened Type I alveolar cells forms the alveolar walls. Type II alveolar cells embedded within the alveolar wall secrete pulmonary surfactant. Wandering alveolar macrophages are found within the alveolar lumen. (The size of the cells and respiratory membrane is exaggerated compared to the size of the alveolar and pulmonary capillary lumens. The diameter of an alveolus is actually about 600 times larger than the intervening space between air and blood.) (b) A transmission electron micrograph showing several alveoli and the close relationship of the capillaries surrounding them.

The alveoli are clusters of thin-walled, inflatable, grapelike sacs at the terminal branches of the conducting airways. The alveolar walls consist of a single layer of flattened Type I alveolar cells (Figure 12-3a). The walls of the dense network of pulmonary capillaries encircling each alveolus are also only one cell thick. The interstitial space between an alveolus and the surrounding capillary network forms an extremely thin barrier, with only 0.5 µm separating air in the alveoli from blood in the pulmonary capillaries.

Furthermore, the alveolar air-blood interface presents a tremendous surface area for exchange. The lungs contain about 300 million alveoli. The total surface area thus exposed between alveolar air and pulmonary capillary blood is about 75 m^2

In addition to the thin, wall-forming Type I cells, the alveolar epithelium also contains Type II alveolar cells (Figure 12-3a). These cells secrete *pulmonary surfactant,* a chemical complex that facilitates lung expansion. Furthermore, defensive alveolar macrophages stand guard within the lumen of the air sacs.

The lungs occupy much of the thoracic cavity

The only muscle within the lungs is the smooth muscle in the walls of the arterioles and the walls of the bronchioles, both of which are subject to control. No muscle is present within the alveolar walls to cause them to inflate and deflate during the breathing process. Instead, changes in lung volume (and accompanying changes in alveolar volume) are brought about through changes in the dimensions of the thoracic cavity.

The lungs occupy most of the volume of the thoracic (chest) cavity, the only other structures in the chest being the heart and associated vessels, the esophagus, the thymus, and some nerves. The outer chest wall (thorax) is formed by 12 pairs of curved ribs, which join the sternum (breastbone) anteriorly and the thoracic vertebrae (backbone) posteriorly. The rib cage provides bony protection for the lungs and heart. The diaphragm, which forms the floor of the thoracic cavity, is a large, dome-shaped sheet of skeletal muscle that completely separates the thoracic cavity from the abdominal cavity. It is penetrated only by the esophagus and blood vessels traversing the thoracic and abdominal cavities.

The pleural sac

A double-walled, closed sac called the pleural sac separates each lung from the thoracic wall and other surrounding structures (Figure 12-4). The interior of the pleural sac is known as the pleural cavity. The surfaces of the pleura secrete a thin intrapleural fluid *(intra* means "within"), which lubricates the pleural surfaces as they slide past each other during respiratory movements. Pleurisy, an inflammation of pleural sac, is accompanied by painful breathing, because each inflation and each deflation of the lungs cause a "friction rub."

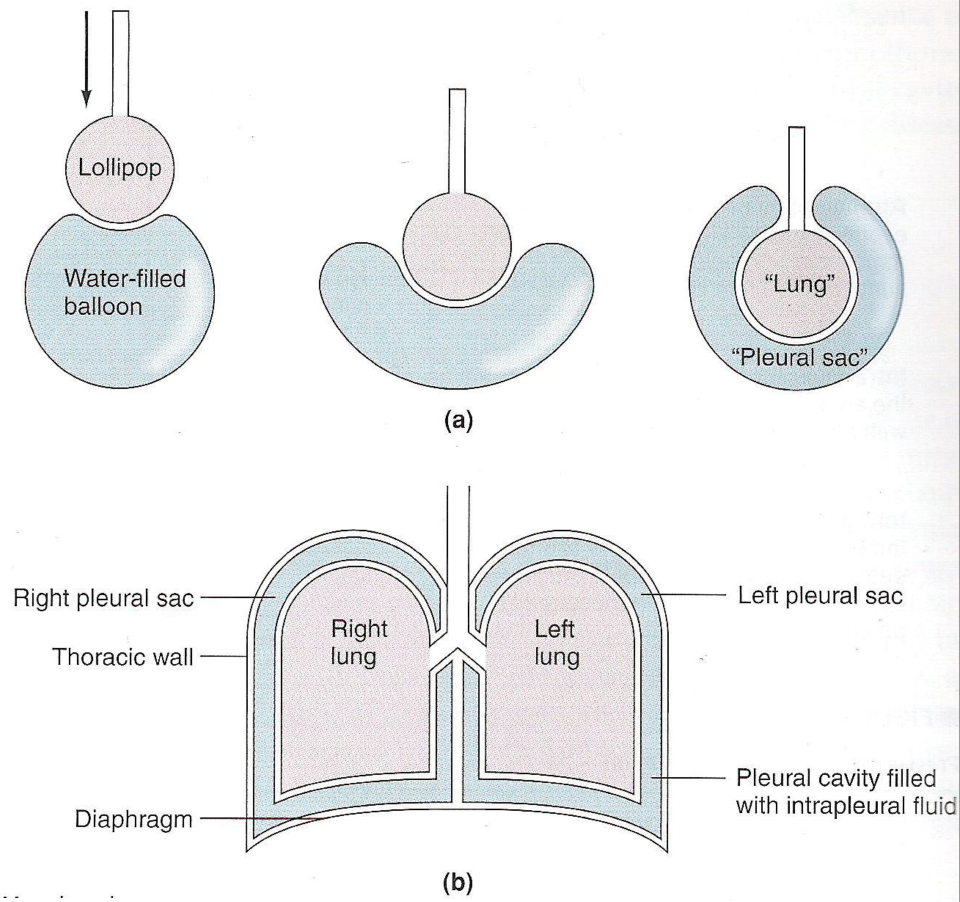


FIGURE 12-4

Pleural sac. (a) Pushing a lollipop into a water-filled balloon produces a relationship analogous to that between each double-walled, closed pleural sac and the lung that it surrounds and separates from the thoracic wall. (b) Schematic representation of the relationship of the pleural sac to the lungs and thorax. One layer of the pleural sac closely adheres to the surface of the lung, then reflects back on itself to form another layer, which lines the interior surface of the thoracic wall. The relative size of the pleural cavity between these two layers is grossly exaggerated for the purpose of visualization.

RESPIRATORY MECHANICS

Air tends to move from a region of higher pressure to a region of lower pressure, that is, down a pressure gradient.

Pressures inside and outside the lungs

Air flows in and out of the lungs during the act of breathing by moving down alternately reversing pressure gradients established between the alveoli and atmosphere by cyclic respiratory muscle activity. Three different pressure considerations are important in ventilation **(**Figure 12-5):

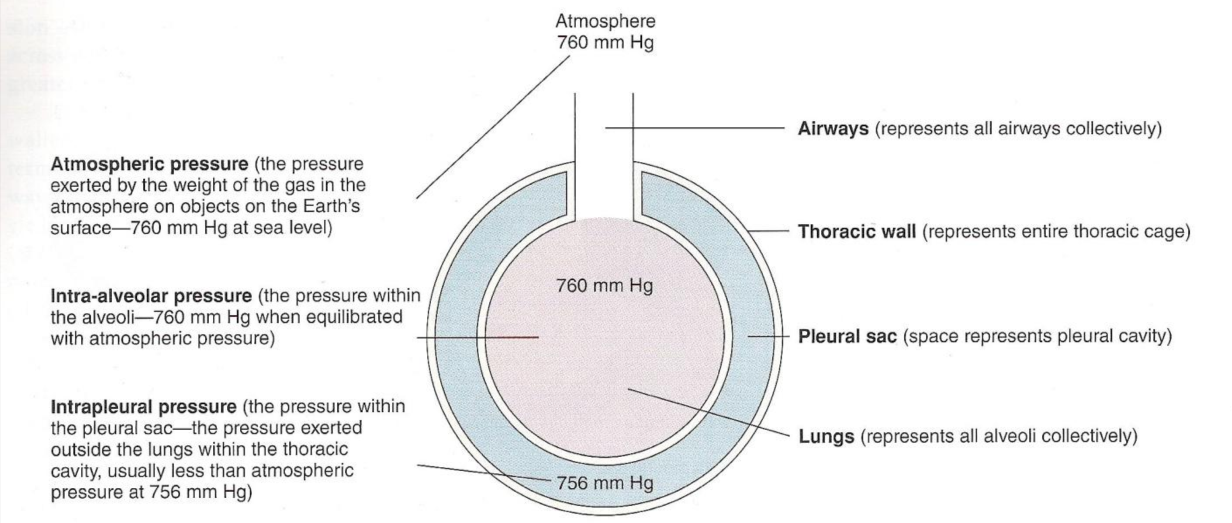


FIGURE 12-5

Pressures important in ventilation

1. Atmospheric (barometric) pressure: at sea level it equals 760 mm Hg.
2. Intrapleural pressure is the pressure within the pleural sac. It is the pressure exerted outside the lungs within the thoracic cavity. The intrapleural pressure is usually less than atmospheric pressure, averaging 756 mm Hg at rest.
3. Intra-alveolar pressure is the pressure within the alveoli. Because the alveoli communicate with the atmosphere through the conducting airways, air quickly flows down its pressure gradient any time intra-alveolar pressure differs from atmospheric pressure; airflow continues until the two pressures equilibrate (become equal).

Intrapleural pressure does not equilibrate with atmospheric or intra-alveolar pressure, because there is no direct communication between the pleural cavity and either the atmosphere or the lungs. Because the pleural sac is a closed sac with no openings, air cannot enter or leave despite any pressure gradients that might exist between it and surrounding regions.

The lungs are normally stretched to fill the larger thorax.

The thoracic cavity is larger than the unstretched lungs. However, two forces-the *intrapleural fluid's cohesiveness* and the *transmural pressure gradient-hold* the thoracic wall and lungs in close apposition, stretching the lungs to fill the larger thoracic cavity.

INTRAPLEURAL FLUID'S COHESIVENESS

The water molecules in the intrapleural fluid resist being pulled apart because they are polar and attracted to each other. The resultant cohesiveness of the intrapleural fluid tends to hold the pleural surfaces together. Thus the intrapleural fluid can be considered very loosely as a "stickiness" or "glue" between the lining of the thoracic wall and the lung. This relationship is partly responsible for the fact that changes in thoracic dimension are always accompanied by corresponding changes in lung dimension; that is, when the thorax expands, the lungs-being stuck to the thoracic wall by the intrapleural fluid's cohesiveness-do likewise. An even more important reason that the lungs follow the movements of the chest wall is the transmural pressure gradient that exists across the lung wall.

TRANSMURAL PRESSURE GRADIENT

The intra-alveolar pressure, equilibrated with atmospheric pressure at 760 mm Hg, is greater than the intrapleural pressure of 756 mm Hg, so a greater pressure is pushing outward than is pushing inward across the lung wall. This net outward pressure differential, the transmural pressure gradient, pushes out on the lungs, stretching, or distending them *(trans* means "across"; *mural* means "wall") **(**Figure 12-7). Because of this pressure gradient, the lungs are always forced to expand to fill the thoracic cavity.

PNEUMOTHORAX

Normally, air does not enter the pleural cavity, because there is no communication between the cavity and either the atmosphere or the alveoli. However, if the chest wall is punctured (for example, by a stab wound or a broken rib), air flows down its pressure gradient from the higher atmospheric pressure and rushes into the pleural space (Figure 12-8a). The abnormal condition of air entering the pleural cavity is known as pneumothorax ("air in the chest"). Intrapleural and intra-alveolar pressure are now both equilibrated with atmospheric pressure, so a transmural pressure gradient no longer exists across the lung wall. With no force present to stretch the lung, it collapses to its unstretched size (Figure 12-8b). Similarly, pneumothorax and lung collapse can occur if air enters the pleural cavity through a hole in the lung produced, for example, by a disease process (Figure 12-8c).

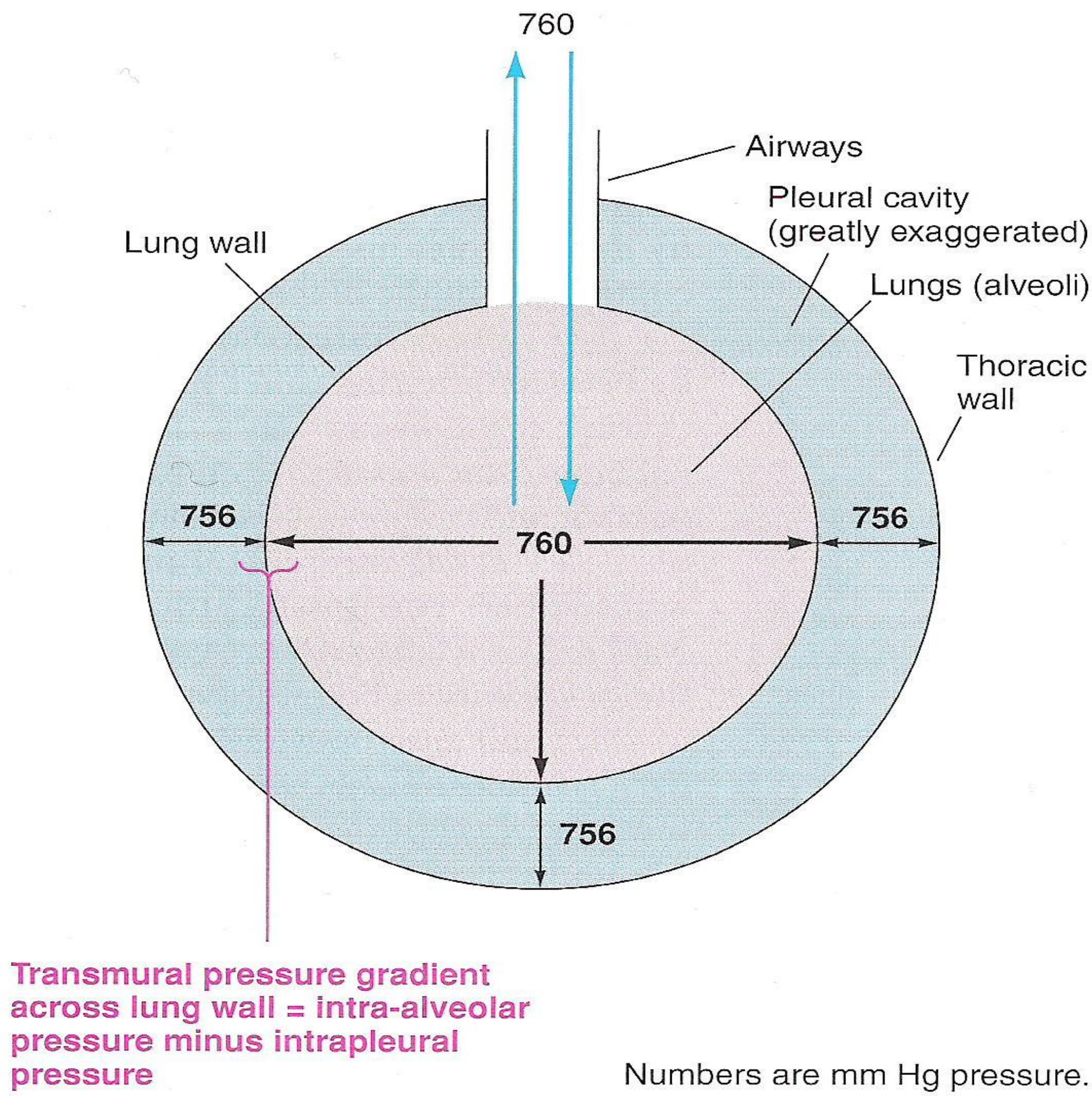
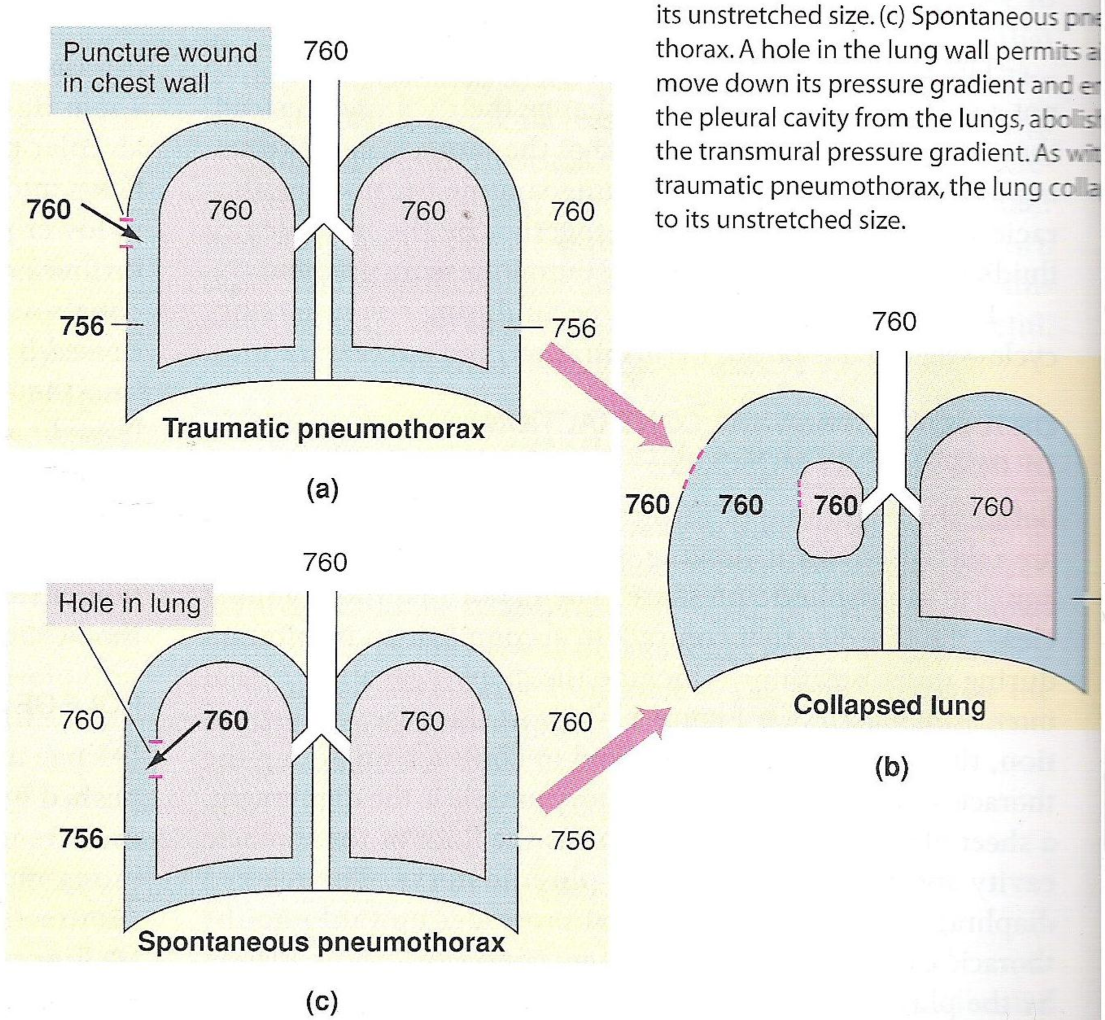


FIGURE 12-7

Transmural pressure gradient. Across the lung wall, the intra-alveolar pressure of 760 mm Hg pushes outward, while the intrapleural pressure of 756 mm Hg pushes inward. This 4-mm Hg difference in pressure constitutes a transmural pressure gradient that pushes out on the lungs, stretching them to fill the larger thoracic cavity.

FIGURE 12-8

Pneumothorax. (a) Traumatic pneumothorax. A puncture in the chest wall pem air from the atmosphere to flow down its pressure gradient and enter the pleura cavity, abolishing the transmural pressure gradient. (b) When the transmural pres gradient is abolished, the lung collapses its unstretched size. (c) Spontaneous pn thorax. A hole in the lung wall permits a move down its pressure gradient and e the pleural cavity from the lungs, abolis the transmural pressure gradient. As wi traumatic pneumothorax, the lung colla to its unstretched size.



Numbers are mm Hg pressure.