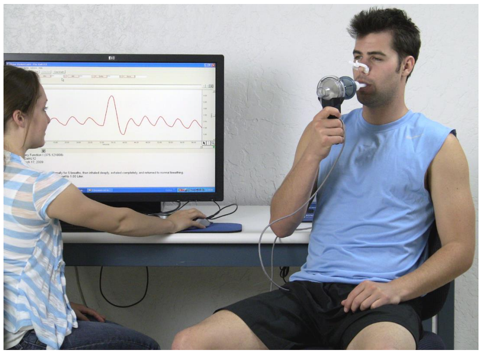
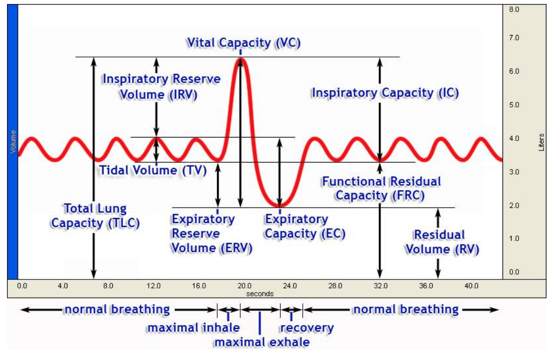
Richard Pflanzer, Ph.D.
Associate Professor Emeritus
Indiana University School of Medicine
Purdue University School of Science

William McMullen
Vice President, BIOPAC Systems, Inc.





I. Introduction

All animals require oxygen to carry out cellular processes of energy transformation essential for life. During cellular metabolism, oxygen is consumed when nutrients such as protein, carbohydrate, and fat are oxidized, and carbon dioxide is produced as a gaseous waste product. Collectively, the processes whereby oxygen is taken up from the atmosphere, delivered to body cells, and consumed, and the processes of producing carbon dioxide and delivering it to the lungs for excretion into the atmosphere constitute *respiration*.

Processes of respiration fall into one of three categories: external respiration, gas transport, and internal respiration. *External respiration* refers to mechanisms by which a person obtains oxygen from the external environment and eliminates carbon dioxide into the external environment. *Gas transport* refers to mechanisms used to distribute oxygen to and remove carbon dioxide from cells. *Internal respiration* refers to the chemical reactions of cellular metabolism in which oxygen is consumed and carbon dioxide is produced. In this lesson we will focus on mechanisms of human external respiration.

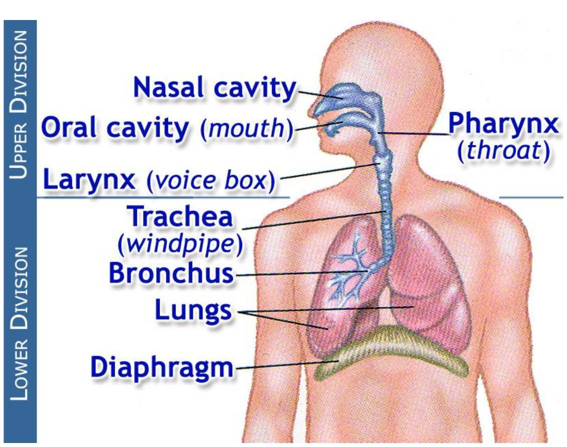


Fig. 12.1 The Respiratory System

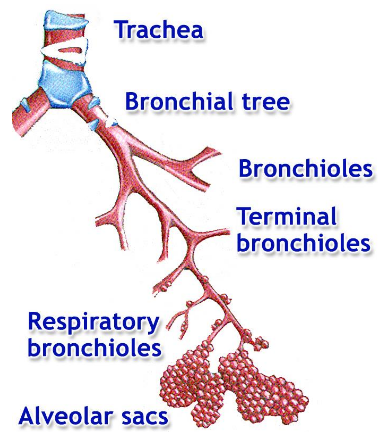


Fig. 12.2 The Respiratory Tree

The human respiratory system (Fig. 12.1) consists of an upper division and a lower division. The *upper division* is made up of the nasal and oral cavities, the pharynx (throat,) and the larynx (voice box). The *lower division* consists of a system of sequentially arranged and progressively smaller airways that resemble an inverted tree. Often called the respiratory tree (Fig. 12.2,) it consists of the trachea (wind pipe,) a right and a left primary bronchus, the lobar bronchi, segmental bronchi, sub-segmental bronchi, terminal bronchioles, respiratory bronchioles, alveolar ducts, alveolar sacs, and individual alveoli. Gas exchange with the blood occurs only in the smaller, thin-walled terminal parts of the tree beginning with the respiratory bronchioles. The remainder of the respiratory tree, and the entire upper division, collectively comprise *anatomical dead space*, space that is ventilated but plays no direct role in gas exchange.

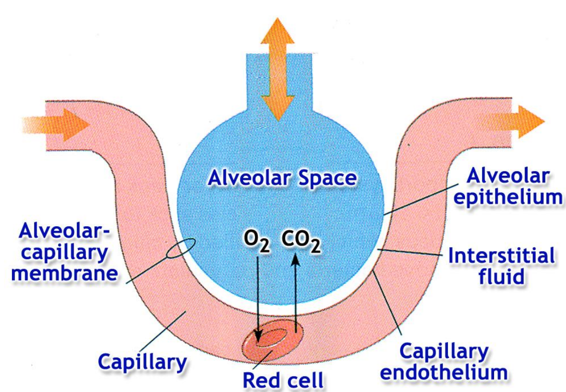


Fig. 12.3 Pulmonary Gas Exchange

Gas exchange between the air in the lung and the blood is a process of simple diffusion (Fig. 12.3). A gas diffuses from a region of higher concentration to a region of lower concentration, or, from an area of higher partial pressure to an area of lower partial pressure. Partial pressure is simply a way of expressing the concentration of gas molecules. It is the pressure exerted by a gas when it is in a mixture with other gases, and is equal to the pressure the same volume of the gas would exert if no other gases were present. The partial pressure of a gas is easily computed if its percentage of the gas mixture and the total pressure of the mixture is known. For example, the atmosphere at sea level exerts a pressure of 760 mm of Hg. If oxygen were to make up 20% of the atmosphere, its partial pressure would be 20% of 760 mm of Hg, or 152 mm of Hg.

Blood transports gases to and from the bodyŝ cells. The respiratory system supplies oxygen to the blood, and removes carbon dioxide from the blood. Most of the gas exchange occurs at the level of the alveoli and the process is completely dependent on the maintenance of gas partial pressures favorable for adequate diffusion of oxygen and carbon dioxide. During inspiration (inhalation) the alveoli enlarge and take in fresh air. During expiration (exhalation) the alveoli get smaller, forcing some of the air back out into the atmosphere. The process of continually and cyclically moving air into and back out of the respiratory tree is called *pulmonary ventilation*. This process serves to maintain favorable partial pressures of oxygen and carbon dioxide in the alveoli, thereby facilitating oxygen uptake by the blood and carbon dioxide removal from the blood.

The mechanics of pulmonary ventilation are best understood by applying *Boyle's law*, which states the volume of a given quantity of gas at a constant temperature varies inversely with the pressure of the gas. In other words, as the volume of a gas at constant temperature increases, the pressure of the gas decreases. If the volume instead decreases, then the pressure increases. Mathematically, the product of the pressure and volume of a gas at constant temperature is itself a constant (PV = K). Ignoring units, if P = 6 and V = 3, then K = 18. If P decreases to 2, then V must increase to 9 because the value of K is 18 and constant as long as the temperature is constant.

The lungs are enclosed by the thoracic cage, which is comprised of the sternum, ribs, vertebral column, and the diaphragm (Fig. 12.1). The tissues of the thoracic cage form the thoracic cavity that is partitioned into smaller cavities by membranes. Each lung is covered with a thin membrane called the visceral pleura. At the root of each lung, where the bronchi enter, the visceral pleura is reflected back around the lung to form the parietal pleura, a lubricating membrane which lines the thorax and covers part of the diaphragm (Fig. 12.4). Normally, each lung completely fills its pleural cavity formed by the reflection of the visceral pleura. The pleural membranes allow the lung to slide freely within the pleural cavity during the respiratory cycle. The space between visceral and parietal pleura, called the pleural space, is only a potential space. Normally, only a thin layer of lubricating fluid separates the two layers of pleura. The pleural cavities are airtight and form part of the thoracic cavity; however, the interior of the lungs is open to the atmosphere via the airways. Therefore, whenever the thoracic cavity enlarges, the pleural cavities along with the lungs also enlarge.

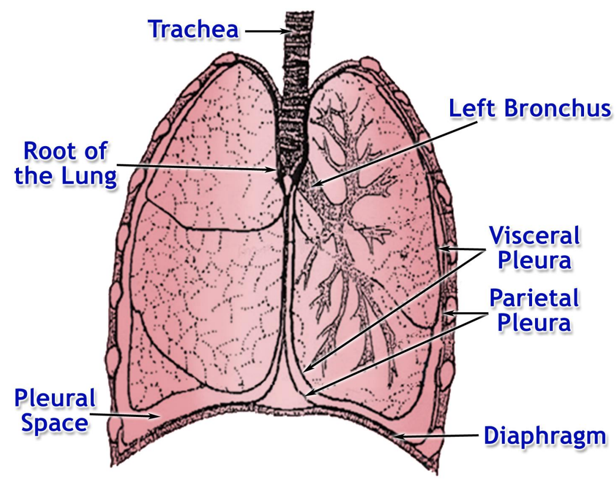


Fig. 12.4 Pleural Cavities (frontal aspect)

Changes in the volume of the thorax are produced by contraction of skeletal muscles collectively called respiratory muscles. They are arbitrarily divided into two groups. *Inspiratory muscles* contract and increase thoracic volume. The diaphragm and the external intercostals muscles are examples. *Expiratory muscles* contract and decrease thoracic volume. Examples include the internal intercostals muscles and the abdominal muscles.

At the beginning of inspiration, the thoracic cavity is enlarged by contraction of the diaphragm and the external intercostals (Fig. 12.5). The diaphragm, normally dome-shaped at rest, becomes flatter when its muscle fibers contract, thereby increasing thoracic volume. The external intercostals elevate the ribs, a kind of bucket-handle lift that increases the diameter, and hence the volume of the thorax. An increase in thoracic volume is accompanied by an increase in intrapulmonic volume, and, according to Boyleŝ law, a decrease in intrapulmonic pressure. As soon as intrapulmonic pressure falls below atmospheric pressure, air flows down the pressure gradient from the atmosphere through the airways and into the expanded air spaces in the lungs, continuing to flow until intrapulmonic pressure is again equal to atmospheric pressure (Fig. 12.5). At the end of inspiration, intrapulmonic pressure equals atmospheric pressure and airflow ceases even though intrapulmonic volume is larger than at the beginning of inspiration.

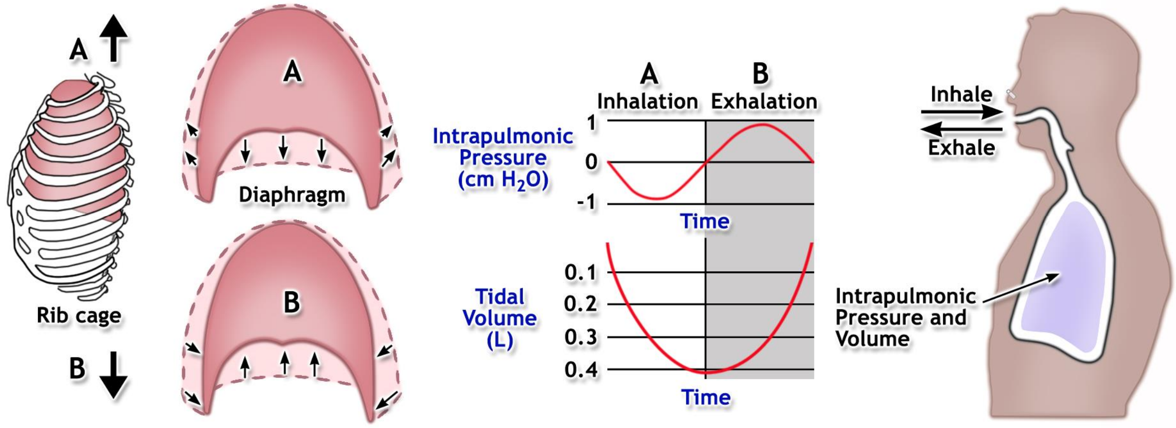


Fig. 12.5 Intrapulmonic pressure and volume changes during one respiratory cycle

Expiration begins when the inspiratory muscles relax. The diaphragm returns to its resting dome shape, decreasing thoracic and intrapulmonic volume. Relaxation of the external intercostals allows the ribs to fall to their resting position, thereby reducing the diameter, and thus the volume of the thorax and lungs (Fig. 12.5). A reduction in intrapulmonic volume is accompanied by an increase in intrapulmonic pressure. As soon as intrapulmonic pressure increases above atmospheric pressure, air flows down the pressure gradient from the expanded air spaces in the lung through the airways and back into the atmosphere, continuing to flow until intrapulmonic pressure is again equal to atmospheric pressure (Fig. 12.5).

The volume of air a person inhales (inspires) and exhales (expires) can be measured with a **spirometer** (*spiro* = breath, *meter* = to measure). A bell spirometer consists of a double-walled cylinder in which an inverted bell filled with oxygen-enriched air is immersed in water to form a seal (Fig. 12.6). A pulley attaches the bell to a recording pen that writes on a drum rotating at a constant speed. During inspiration, air is removed from the bell and the pen rises, recording an inspired volume. As expired air enters the bell, the pen falls and an expired volume is recorded. The resultant record of volume change vs. time is called a **spirogram**.

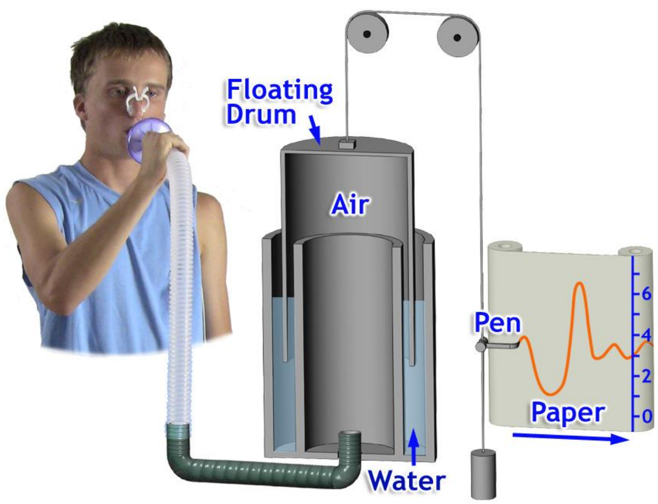


Fig. 12.6 Bell Spirometer

In this lesson, you will use the BIOPAC airflow transducer and the software will convert airflow to volume, thus approximating the volume measurements from a spirometer. Air flows through a sealed head which is divided in half by a fine mesh screen. The screen creates a slight resistance to airflow resulting in a higher pressure on one side than the other. A Differential Pressure Transducer measures the pressure difference, which is proportional to the airflow, and converts it to a voltage, which is then recorded by the BIOPAC MP unit. After the airflow recording is complete, the software calculates volume by integrating the airflow data. This integration technique is a simple method for obtaining volume but is very sensitive to baseline offset. For this reason the calibration and recording procedures must be followed **exactly** to obtain accurate results.

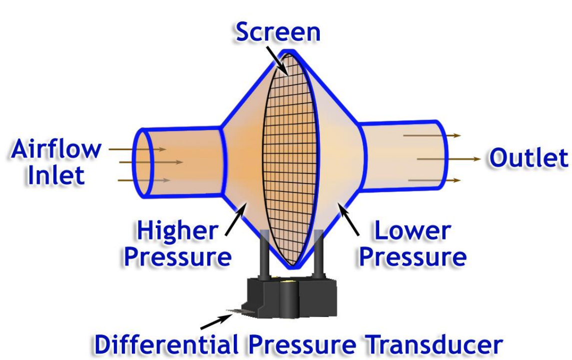


Fig. 12.6b Airflow Transducer

There are four non-overlapping primary compartments of total lung capacity (Fig. 12.7):

1. Tidal volume
2. Inspiratory reserve volume
3. Expiratory reserve volume
4. Residual volume

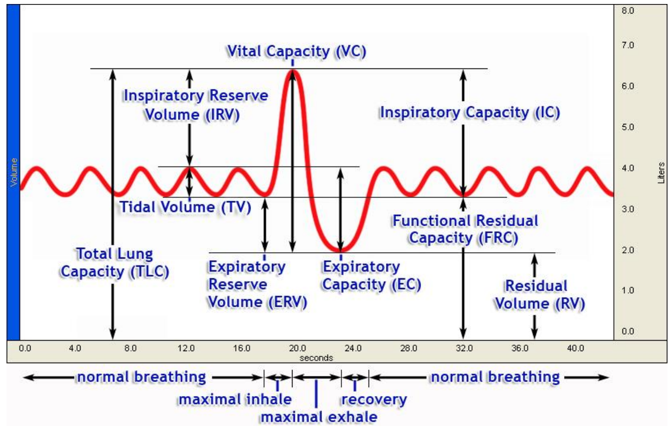


Fig. 12.7 Example of respiratory volumes and capacities

- **Tidal Volume** (TV) is the volume of air inspired or expired during a single breath. When a resting person breathes normally, tidal volume is approximately 500 ml. During exercise, tidal volume can be more than 3 liters.
- **Inspiratory Reserve Volume** (IRV) is the volume of air that can be maximally inhaled at the end of a tidal inspiration. Resting IRV is approximately 3,300 ml in young adult males and 1900 ml in young adult females.
- **Expiratory Reserve Volume** (ERV) is the volume of air that can be maximally exhaled at the end of a tidal expiration. Resting ERV is approximately 1,000 ml in young adult males and 700 ml in young adult females.
- **Residual Volume** (RV) is the volume of gas remaining in the lungs at the end of a maximal expiration. In contrast to IRV, TV, and ERV, residual volume does not change with exercise. Average adult values for RV are 1,200 ml for males and 1,100 ml for females. Residual volume reflects the fact that after the first breath at birth inflates the lungs, they are never completely emptied during any subsequent respiratory cycle.

Pulmonary Capacity is the sum of two or more primary lung volumes. There are five pulmonary capacities, which can be calculated as shown below:

1. **Inspiratory Capacity** (IC) IC = TV + IRV
2. **Expiratory Capacity** (EC) EC = TV + ERV
3. **Functional Residual Capacity** (FRC) FRC = ERV + RV
4. **Vital Capacity** (VC) VC = IRV + TV + ERV
5. **Total Lung Capacity** (TLC) TLC = IRV + TV + ERV + RV

Each of these capacities is represented graphically in Fig. 12.7 above.

Pulmonary volumes and capacities are generally measured when assessing health of the respiratory system because the volume and capacity values change with pulmonary disease. For example, inspiratory capacity is normally 60-70% of the vital capacity.

In this lesson, you will measure tidal volume, inspiratory reserve volume, and expiratory reserve volume. Residual volume cannot be measured using a spirogram or airflow transducer. You will then calculate inspiratory capacity, vital capacity, and the % observed vital capacity to the average values for comparison. Next, you will compare your observed vital capacity with the predicted vital capacity.

The following equations can be used to obtain the predicted vital capacities for men or women of your height and age. Vital capacities are dependent on other factors besides age and height. Therefore, 80% of the calculated values are still considered normal.

Table 12.1

Equations for Predicted Vital Capacity (Kory, Hamilton, Callahan: 1960)	
Male	V.C. = 0.052H ï 0.022A ï 3.60
Female	V.C. = 0.041H ï 0.018A ï 2.69

Where V.C. Vital Capacity in liters
H Height in centimeters
A Age in years

Using the equation in Table 12.1, you can estimate the vital capacity of a 19 year old female who is 167 centimeters tall (about 5ô6ò) as 3.815 liters:

0.041 x (167) ï 0.018 x (19) ï 2.69 = 3.815 liters