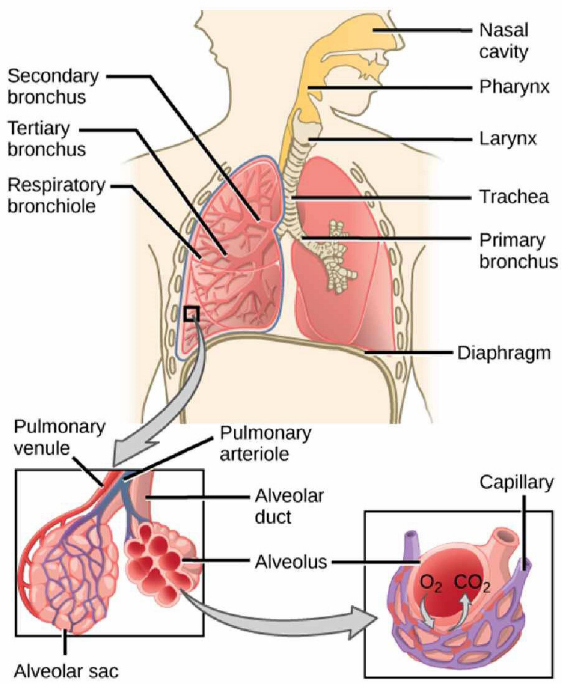
Physics of the Respiratory System

1. Introduction

The respiratory system is a biological system consisting of specific organs and structures used for the process of respiration in an organism. The respiratory system is involved in the intake and exchange of oxygen and carbon dioxide between an organism and the environment.

2. Structure of the Respiratory System

The respiratory system provides oxygen (O_2) to the body's cells while removing carbon dioxide (CO_2), a waste product that can be lethal if allowed to accumulate. There are 3 major parts of the respiratory system:



Upper tract

1. *Nose, mouth* and *nasal cavity* (to warm, filter and moisturize the inspired air).
2. *Larynx*

Lower tract

1. *Trachea* (to flow the inspired air toward the bronchi).
2. *Bronchi* (to furnish air to each lung).
3. *Alveoli* (each bronchioles terminates in several alveolar sacs where the exchanging O_2 and CO_2 between inspired air and blood in alveoli occur)

3. Respiratory System Functions

The functions of the respiratory system can be classified as following:

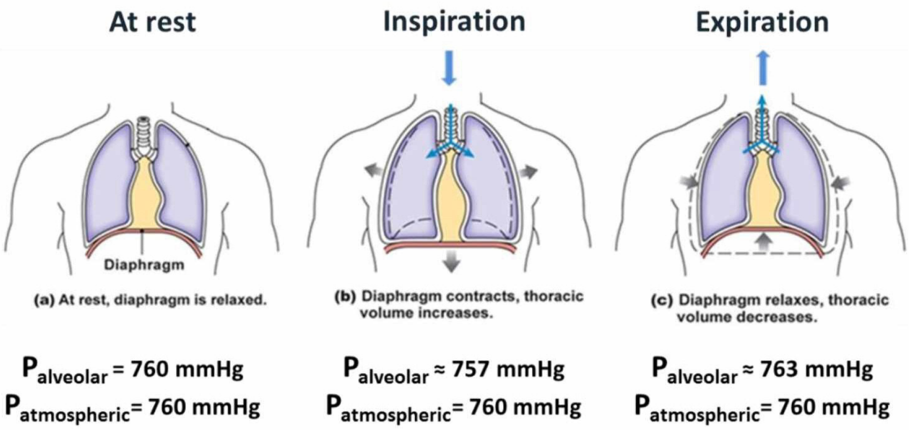
1. *Gas exchange* – O_2 enters blood and CO_2 leaves.
2. *Keeping blood pH* (acidity) constant - Altered by changing blood carbon dioxide levels.
3. *Voice production* - Movement of air past vocal folds makes sound and speech.
4. *Protection* – Removing the dust particles stuck to the moist lining of various air ways.
5. *Thermoregulation* - Heating and cooling of body.
6. *Fluid balance* - Warming and moisturizing the air we breathe.

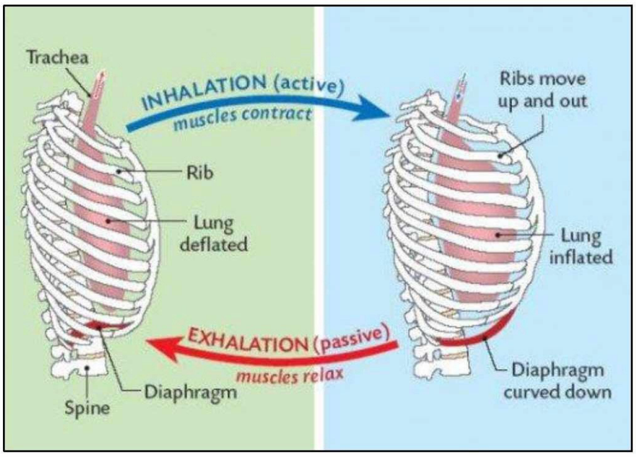
4. Mechanism of Breathing (Ventilation)

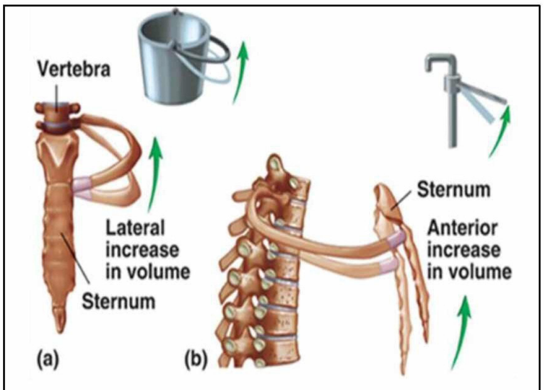
Ventilation process is a mechanical movement of air into (inspiration or inhalation) and out of (expiration or inhalation) the lungs. Air movement is determined completely by the pressure gradients which are produced by thoracic expansion/contraction. Pressure is inversely related to volume of lung volume according to Boyl's law which is given by:

$$P_1V_1 = P_2V_2 = Constant$$

And the flow of air is given by: $Flow = (P_{atmospheric} - P_{alveolar})$







Movement of ribs during inspiration (inhalation)

The lungs can be expanded or contracted in two ways:

a. By elevation and depression of the ribs to increase or decrease the anteroposterior diameter of the chest cavity for inspiration and expiration consequently.
b. By downward and upward movement of the diaphragm to lengthen or shorten the chest cavity for inspiration and expiration consequently.

Variation of pressures during breathing

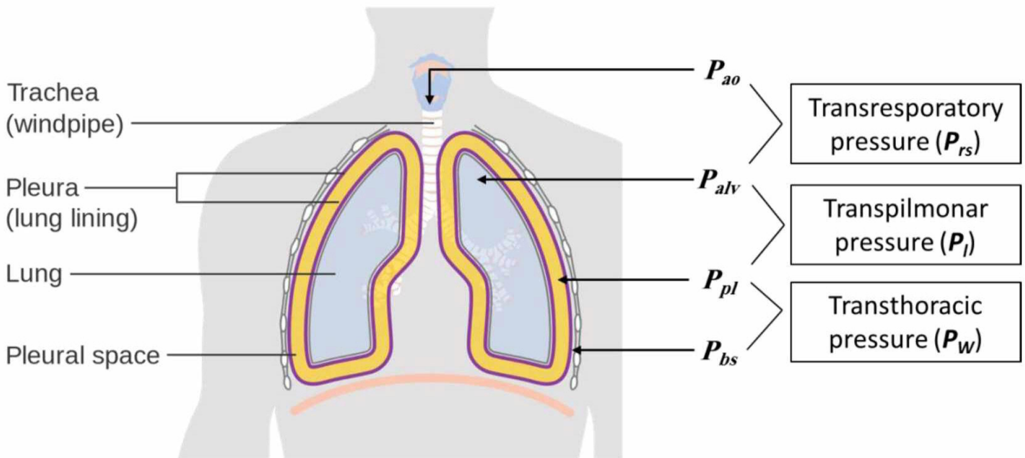
Many pressures, gradients, volumes and flows are involved in breathing process. These pressures are:

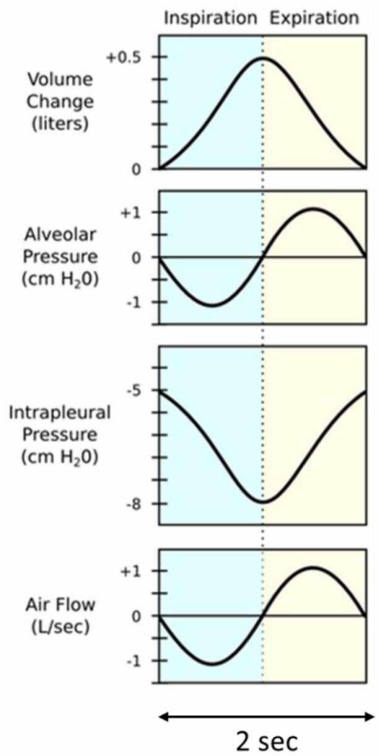
P_{ao} , pressure at the airway opening (mouth pressure);

P_{alv} , pressure in the alveoli (intrapulmonary pressure);

P_{pl} , pressure in the plural space (intrapleural pressure);

P_{bs} , pressure at the body surface





Transrespiratory pressure gradient $(P_{rs}) = P_{alv} - P_{ao}$

- It is responsible for air flow into and out of the lungs.

Transpulmonary pressure gradient $(P_L) = P_{alv} - P_{pl}$

- It is responsible for the degree of the alveolar inflation.

Transthoracic pressure gradient $(P_W) = P_{pl} - P_{bs}$

- It is the difference in pressure across the chest wall, or the total pressure necessary to expand or contract the lungs and chest wall together.

- Changes in flow and volume are related to changes in these pressure gradients, as shown in the graphs on the right.
- Positive transpulmonary pressure is important to keep the lungs inflated at all times.

5. Factors Affecting Breathing Process

5.1. Lung compliance

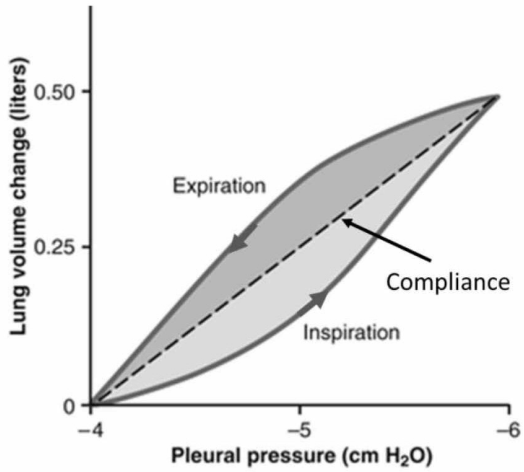
During inspiration, a pressure is applied and the lung is stretched. Greater pressure causes greater stretch until maximum inflation (stretching) is reached as a result to existence of the elastic and collagen fibers which provide a resistance to lung stretch.

Lung compliance is the ability of the lungs to stretch during inspiration. It is given by the change in volume produced by a given change in pressure (the slope of the pressure-volume curve).

$$Compliance = \frac{\Delta V}{\Delta P} \qquad \frac{Litter}{cm\ H_2O}$$

[For typical adult → Compliance = 0.18 – 0.27 (Litter/cm H_2O)]

- Important point is the volume at a given pressure during expiration is always larger than during inspiration.



- The **greater** the compliance, the **easier it is for a change in pressure to cause** (Floppy lung).
- A **lower**-than-normal compliance means the lungs and thorax are **harder to expand** (Stiff lung).

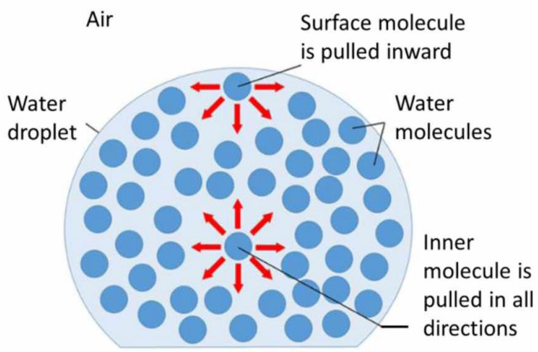
Disease

In *emphysema* the divisions between the alveoli break down, producing larger lung spaces. The lung become more compliant (a small change in pressure produces a larger than normal change in the volume; floppy lung). A person who has emphysema is unable to blow out a candle.

5.2. Surface tension

A thin film of liquid lines the alveoli and the surface tension of this film is another important factor in the pressure-volume relationship of the lung.

The surface tension arises because the attractive forces between adjacent molecules of the liquid are much stronger than those of between the liquid and the gas. As a result, the liquid surface area becomes as small as possible (eg. Droplet of water).



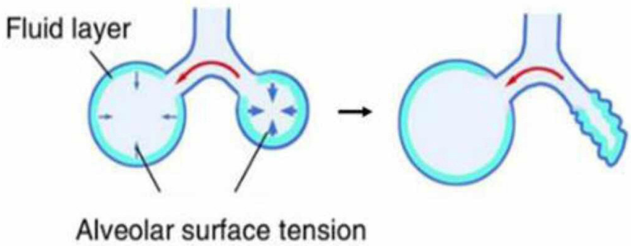
For a bubble, the pressure (P), radius (r) and surface tension (T) is given by Laplace's law;

$$P = \frac{4T}{r} \qquad \text{Laplace's Law}$$

For an alveoli (which is like bubble in shape), at the interface between the liquid that lining it and the alveolar gas, intermolecular forces in the liquid tend to cause the area of the lining to shrink (the alveoli tend to get smaller).

When the Laplace's law is applying on the alveoli (which is like bubble in shape), during inspiration the following events will happen:

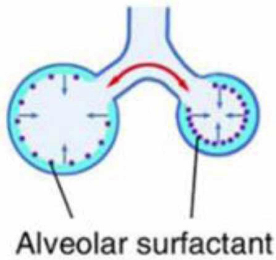
- The radius of the alveoli will increase.
- According to Laplace's Law, the pressure will reduce.
- The pressure is greater in the smaller alveoli.
- The smaller alveoli will collapse.



But in fact, the surface tension does not cause the collapse of alveoli, due to existence of the pulmonary surfactant in the alveoli's inter wall. The pulmonary surfactant (which is a combination of phospholipid and protein secreted by Type II alveolar cells), lowers the surface tension sufficiently by getting between water molecules, reducing their ability to attract each other by hydrogen bonding.

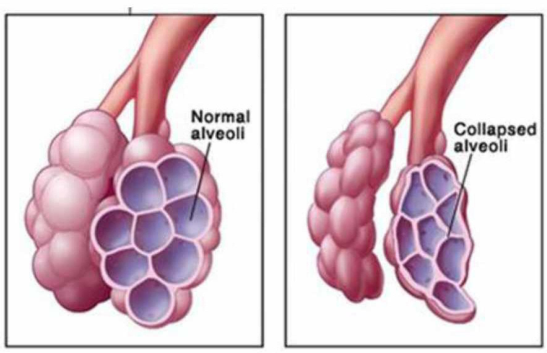
The function of the pulmonary surfactant is:

- Decrease the surface tension when the radius is decreasing.
- Increase the surface tension when the radius is increasing.
- The aim is to keep the pressure is constant.



Disease

The absence of surfactant in the lungs of some newborn infants, especially premature, is the cause of the respiratory distress syndrome (RDS). This disease kills more babies than other disease.



5.3. Airways resistance

The resistance of airway to the air flow in the lungs is analogous to the resistance to the current in the electrical circuit, voltage replaced by pressure difference ΔP and current replaced by rate of flow $\Delta V/\Delta t = V$.

Air resistance $\rightarrow R_g = \frac{\Delta P}{\Delta V/\Delta t} \quad (\frac{cm\ H_2O}{Litter/Sec})$, Typical value for R_g = 3.3 cm H_2O/ (Litter/Sec)

The air passages provide resistance like; *mucous* and *diameter* of the air passage, especially in the upper airway passages, where (diameter ↓ = resistance ↑)

Disease
In asthma, the basic problem is expiratory difficulty due to increased airway resistance. This resistance is due to swelling and mucus in the smaller airways and due to contraction of the smooth muscle around the large airways.

Normal bronchiole **Asthmatic bronchiole**

6. How the Blood and Lungs Interact?

The primary purposes of breathing are to bring a fresh supply of O_2 to the blood in the lungs and to dispose of the CO_2. To understand the gas exchange processes it is necessary to review the physical laws that governed it.

a. Ventilation-Perfusion ratio (Volumetric flow rates)

Two general processes are involved in gas exchange in the lungs:
- Ventilation (V): the air that reaches the alveoli
- Perfusion (Q): the blood that reaches the alveoli via the capillaries

$$Ventilation - Perfusion\ ratio = \frac{amount\ of\ air\ that\ reaching\ alveoli\ per\ minute}{amount\ of\ blood\ that\ reaching\ the\ alveoli\ per\ minute} = \frac{4\ L/min}{5\ L/min}$$

The typical value of ventilation-perfusion ratio is 0.8.

- Good ventilation & good perfusion, the ratio = 0.8 (as in the 90% of the normal lung)
- Good ventilation & poor perfusion, the ratio > 0.8 (as when the blood flow to part of a lung is blocked by a clot)
- Poor ventilation & good perfusion, the ratio < 0.8 (as when the air passages in the lungs are obstructed as in pneumonia)

These two variables, V & Q, control and determine the concentration of O_2 and CO_2 in blood

b. Dalton's law

Dalton's law states that in a mixture of non-reacting gases, the total pressure exerted is equal to the sum of the partial pressures of the individual gases. The partial pressure of a gas in a mixture of gases is directly related to:

- The concentration of that gas in the mixture.
- The total pressure of the mixture.

The mathematical expression of this law as following: $P_{tot} = P_1 + P_2 + P_3 + \dots + P_n$

Partial pressure of a gas depends on fractional concentration of the gases:

$$P_{gas} = \%_{gas} \times P_{tot}$$

c. Diffusions law

It is the movement of molecules of a particular type of a gas from higher concentration to lower concentration. Diffusion depends on the speed of molecules, it is more rapid if the molecules are light and it increases with temperature.

d. Henrys law

Quantity of a gas that will dissolve in solution is proportional to the partial pressure and the solubility coefficient.

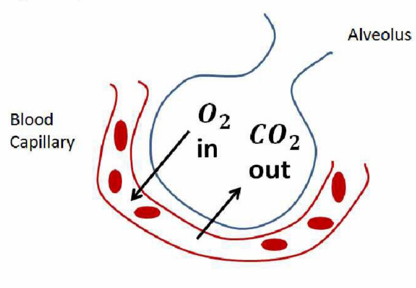
Mechanism of the gas exchange

During normal breathing the fresh supply of air does not enter the alveoli which are still filled with stale air from previous breaths, but the following processes are take place.

1. According to **ventilation-perfusion ratio** the concentrations of O_2 and CO_2 have been determined.
2. According to **diffusion law**, and because of its higher concentration, the fresh O_2 rapidly diffuses through the stale air to reach the internal surface of the alveoli.
3. Because the concentration of O_2 in the alveolar air is higher than that in the blood of pulmonary capillaries. So and according to **Daltons law**

$$P_{O_2} \text{ in the alveoli } > P_{O_2} \text{ in the pulmonary capillaries}$$

4. As a result to the difference in partial pressure and **according to Henrys law**, O_2 will be dissolved in the moist alveoli wall and diffuses through into the capillary blood until the PO_2 in the blood is equal to that in the alveoli. This process takes place less than 0.5 sec.

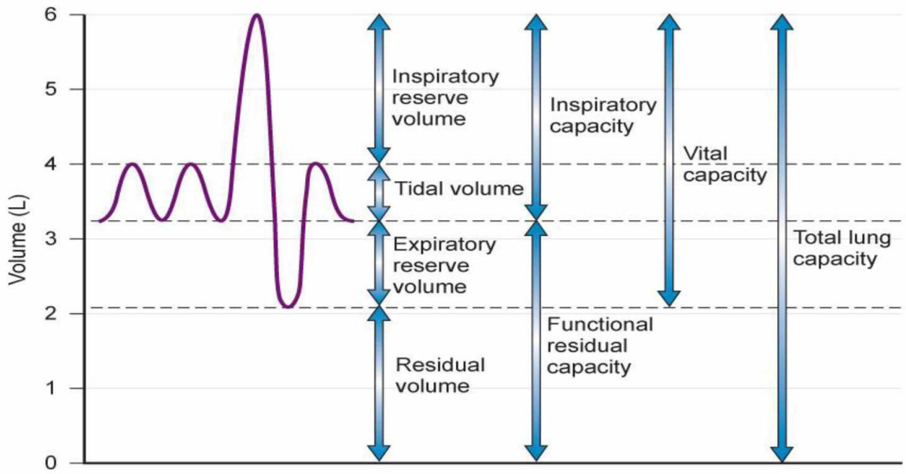


Meanwhile the CO_2 in the blood diffuses even more rapidly into the alveolar air until the P_{CO2} in the blood is the same as in the alveolar air.

7. Volumes of air exchanged in pulmonary ventilation

The volumes of air moved in and out of the lungs and remaining in them are matters of great important. They must be normal so that a normal exchange of O_2 and CO_2 can take place between alveolar air and pulmonary capillaries.

An apparatus called a spirometer is used to measure the volume of air exchanged in breathing. The figure below shows a typical curve for normal breathing contains lung volumes and capacities.



Lung volumes: The four non-overlapping components of the total lung capacity.

There are four volumes:

1. <u>Tidal volume</u> (V_t) / The volume of air inspired or expired in an unforced respiratory capacity.
2. <u>Inspiratory reserve volume</u> (IRV)/ The maximum volume of air that can be inspired during forced breathing in addition to tidal volume.
3. <u>Expiratory reserve volume</u> (ERV)/ The maximum volume of air that can be expired during forced breathing in addition to tidal volume.
4. <u>Residual volume</u> (RV) / The volume of air remaining in the lungs after a maximum inspiration.

Lung Capacities: Measurements that are the sum of two or more lung volumes.

There are four lung capacities:

1. <u>Total lung capacity</u> (TLC) / The total amount of air in the lungs after a maximum inspiration.
2. <u>Vital capacity</u> (VC) / The maximum amount of air that can be expired after a maximum inspiration.
3. <u>Inspiratory capacity</u> (IC) / The maximum amount of air that can be inspired after a normal tidal expiration.
4. <u>Functional residual capacity</u> (FRC) / The amount of air remaining in the lungs after a normal tidal expiration.