The Physics of the Lungs and Breathing

The human " machine " really consists of billions of very small "engines " the living cells of the body .Each of these a miniature engines must be provided with fuel ,O_2 ,and a method of getting rid of the products .

The blood and its vessels (cardiovascular system) serve as the transport for these engines .The lungs (pulmonary system) serve as the supplier of O_2 and disposes of the main by product - CO_2 .The blood takes the O_2 to the tissues and removes the CO_2 from the tissues; it must come in close contact with the air in the lungs in order to exchange its load of CO_2 for a fresh load of O_2 .

The function of the Lungs

1. Exchanging of O_2 ands CO_2 .
2. Keeping the PH (acidity) of the blood constant .
3. Heat exchange .
4. Keeping the fluid of the body balance by warming and moisturizing the air we breath .
5. Controlled the flow of air for talking , coughing ,sneezing , sighing , laughing , and sniffing .
6. Voice production .

Breathing:

We breath about 6 liters of air per minute .Men breath about 12 times per minute at rest ,Women breath about 20 times per minute ,Infants breath about 60 times per minute .The air we inspired is about 80% N_2 and 20% O_2 .Expired air is about 80% N_2 ,16% O_2 and 4% CO_2 .We breath about 10 Kg of air each day .Of this the lungs absorbs 400 liters of O_2 (0.5 Kg) and release a slightly smaller amount of CO_2 .Each time we breath , about 10^{22} molecules of air enter our lungs .Each liters of air contain about 6 x10^{23}molecules (*Avogadro's number*).

Air ways

The principal air passage into the lungs are shown in figure (1). Air normally enters the body through the nose where it is warmed, filtered and moisturized .The air then passes through trachea .The trachea divides into two to furnish air to each lung through the bronchi. Each bronchus divides and re divides about 15 times, the resulting terminal bronchioles supply air to millions of small sacs called *alveoli*.

The alveoli is small interconnected bubbles are about 0.2 mm in diameter and have walls only 0.4 μm thick .They expand and contract during breathing ; they are in the exchanging of O_2 and CO_2 .Each alveolus is surrounded by blood so that O_2 can diffuse from the blood into the air in the alveolus .

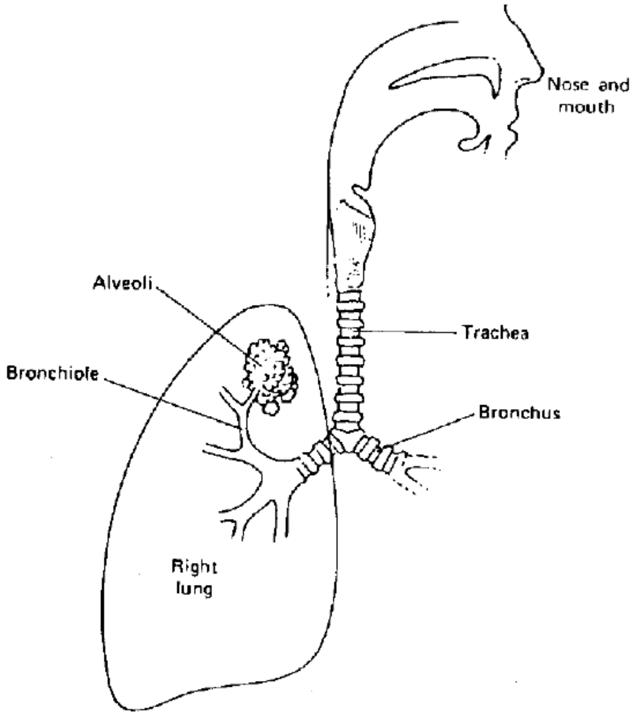


Figure A schematic diagram showing the principal air passages into the lungs.

The Physics of Exchanging of Gas between the Lungs and the Blood

The transfer of O_2 and CO_2 into and out of the blood is controlled by the physical law of diffusion .All molecules are continually in motion. In gases and liquids , and to certain extent even in solids , the molecules do not remain in one direction .Molecules of a particular type diffuse from region of higher concentration to a region of lower concentration until the concentration is uniform In the lungs we are concerned with diffusion in both gas and liquids .In the O_2 and CO_2 exchange in the tissues we are concerned only with diffusion in liquids .The molecules in a gas at room temperature move at about the speed of sound . Each molecule collides about 10^{10} times each second with neighboring molecules.

The distance D of molecule will travel from its origin after N collisions is

$$\mathbf{D = \lambda\sqrt{N}}$$

Where λ is the mean free path.

λ is defined as the average distance between collision .

in air $\lambda = 10^{-7}$ m , in tissue $\lambda = 10^{-11}$ m

<u>Ex</u>. :What is the typical value of D in air and in tissue for an O_2 molecule after 1 sec if $N= 10^{10}$ in air and in tissue $N = 10^{12}$?

Sol..//

In air $D = 10^{-7} (10^{10})^{1/2} = 10^{-2}$ m

In tissue $D = 10^{-11} (10^{12})^{1/2} = 10^{-5}$m

Diffusion depends on the speed of the molecules, the speed of molecules increases with temperature.

Since N is proportional to the diffusion time Δt .

$$N \propto \Delta t$$
$$D \propto \sqrt{\Delta t}$$
$$\Delta t \propto D^2$$

In the lungs the distance to be traveled in air usually a small fraction of a millimeter, and diffusion takes place in a fraction of a second .The diffusion of O_2 and CO_2 in tissue is about 10,000 times slower than it is in air , but the tissue thickness of the molecules must diffuse through in the lungs is very small (0.4µm) and diffusion through the alveolar wall takes place in much less than 1 sec .

To understand the behavior of gases in lungs it is necessary to know *Dalton'* s *law* of partial pressures .*Dalton's law* state that if you have a mixture of several gases , each gas make its own contribution to the total pressure as though it were all alone.

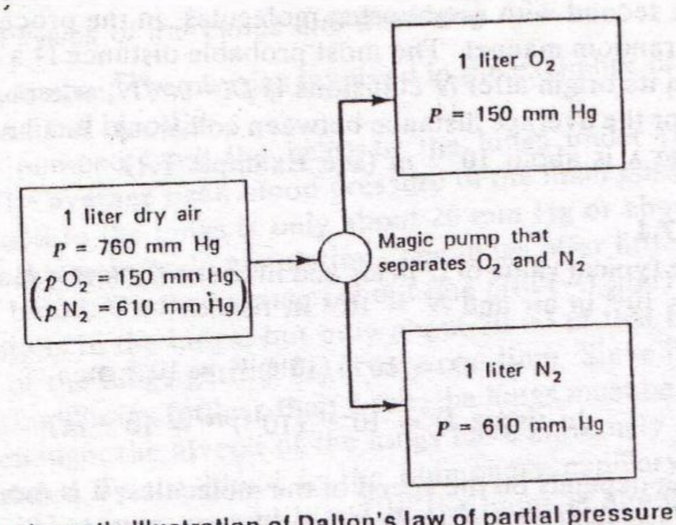


Figure A schematic illustration of Dalton's law of partial pressures. A liter of air at 760 mm Hg pressure can be thought of as a mixture of 1 liter of O_2 at a pressure of 150 mm Hg and 1 liter of N_2 at a pressure of 610 mm Hg.

The pressure exerted by any one of the gases is known as the *partial pressure* of that gas, and the total pressure of these gases is the sum of the partial pressures of the mixture gases.

$$p_{total} = p_{t1} + p_{t2} + p_{t3} \text{ -----}$$

where **p** is a partial pressure

Henry's Law of Solubility of Gases:

Henry 's *law* states that the quantity of a gas going into simple solution at constant temperature is proportional to the pressure .If we have a closed container of blood and CO_2 ,It found that some of O_2 molecules collide with blood and are dissolved .After a while the number of O_2 molecules that are escaping from the blood each second is the same as the number that are entering it .The blood then has a P_{O2} equal to that of the O_2 in contact with it .If P_{O2} in the gas phase is doubled , the amount of O_2 dissolved in the blood will also double . This proportionality is Henry's law of solubility of gases .The amount of gas dissolved in blood varies greatly from one gas to another .Oxygen is not very soluble in blood or water .The different solubility of O_2 and CO_2 in tissue affect the transport of these gases across the alveolar wall. A molecule of O_2 diffuse faster than a molecule of CO_2 because of its smaller mass .

However , because of greater number of CO_2 molecules in solution , the transport of CO_2 is more efficient than the transport of O_2. The mixture of gases in the alveoli is not the same as the mixture of gases in ordinary air .The lungs are not emptied during expiration .During normal breathing the lungs retain about 30 % of their volume at the end of each expiration . This is called the functional residual volume (FRC).At each breath 500 cm³ of fresh air (P_{O2} of 150 mm Hg) mixes with 2000 cm³ of stale air in the lungs to result in alveolar air with a P_{O2} 100 mm Hg .The P_{CO2} in the alveoli is about 40 mm Hg .Expired air includes about 150 cm of relatively fresh air from the trachea that are not in contact with alveolar surface , so expired air has a slightly higher PO_2 and lower P_{CO2} than alveolar air .

The percentages and partial pressures of O_2 and CO_2 in inspired ,alveolar and Expired .

	% O_2	P_{O2} (mmHg)	% CO_2	P_{CO2} (mmHg)
Inspired	20.9	150	0.04	0.3
Alveolar air	14.0	100	5.6	40
Expired air	16.3	116	4.5	32

Measurement of Lungs Volume:

The spirometer is an instrument used to measure airflow into and out the lungs and record it on a graph of volume versus time.

This instrument consists of a counter balanced bell free to move in the vertical plane, as shown in figure (3) . It has a water –seal so that it forms an airtight chamber of variable volume.The changes in volume of this chamber are recorded on a chart.

When breathing through the mouth piece into the spirometer with a nose clip applied, the air in the lungs, air passage and the spirometer is a closed systems .

Thus, when the lungs volume increases in the inspiration the volume of gas in the spirometer is reduced ,and when the lung volume decreases in expiration , the spirometer volume increases .

-Tidal volume: is defined as the amount of air in or out per breath .

-Inspiratory reserve volume .:is the additional amount of air which can be inspired at the end of a normal inspiration .

-Expiratory Reserve volume : is the additional amount of air which can be expired at the end of a normal expiration .

- Residual volume :is the amount of air remaining in the lungs at the end of a forced expiration .

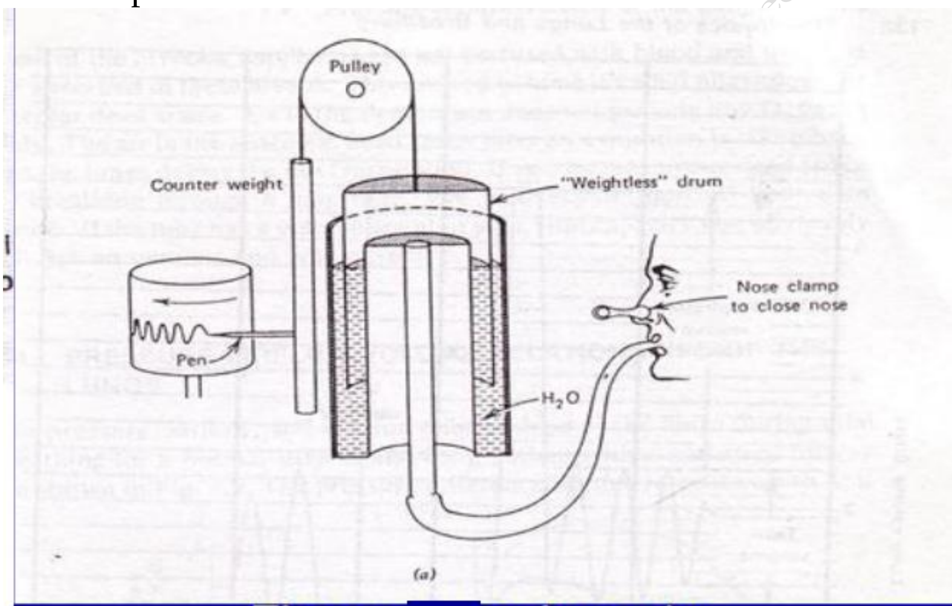


Figure [redacted] spirometer

Capacity

By adding all four types of volume together, we get the total lung capacity . If we add only Inspiratory reserve volume, tidal volume ,and expiratory reserve volume we get the vital capacity .

If we add only the expiratory reserve volume and residual volume, we get functional residual capacity (FRC).

Ventilation

Ventilation is the continuous process off moving air in and out off the lungs..

Ventilation is usually expressed in volume per unit minute,, or liters per minutes ..

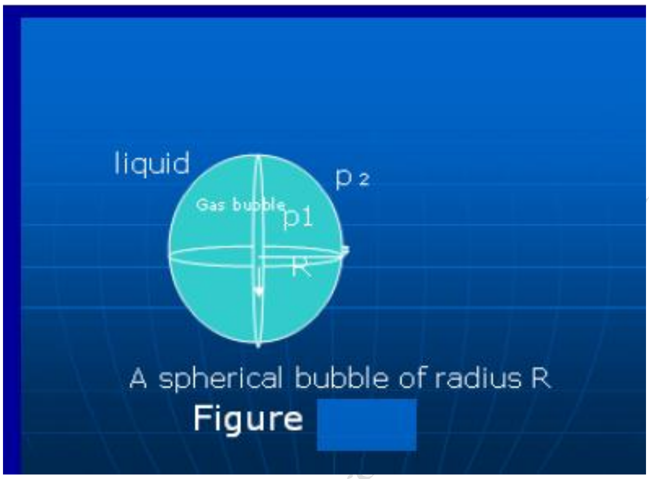
Surface tension: is define as the force per unit length acting across any line drawn in the surface and tending to pull the surface apart across the line .

S=F/L (Newten/m)

Surface tension of a liquid can be regarded as the potential energy per unit area of the surface.

Excess pressure inside a spherical air bubble:

Consider a spherical air bubble off radius R ,, inside a liquid off surface tension S ..



P_1 is the pressure inside the bubble

P_2 is the pressure outside the bubble

$P_1 > P_2$

The bubble divided into two hemisphere

The circumference off the circle = $2 \pi R$

Surface tension will exert a down ward force F $=2\pi RS$ on the upper hemisphere ,, and equal upward force on lower hemisphere ..

$(P_1 - P_2)\pi R^2$ is the downward force on the upper hemisphere is balance by a thrust due to the excess pressure $(P_1 - P_2)$ ..

At equilibrium …..$(P_1 - P_2)\pi R^2 = 2\pi RS$

$P_1 - P_2 = 2S/R$

For spherical drop off water ,, the excess pressure is

$P_1 - P_2 = 4S/R$

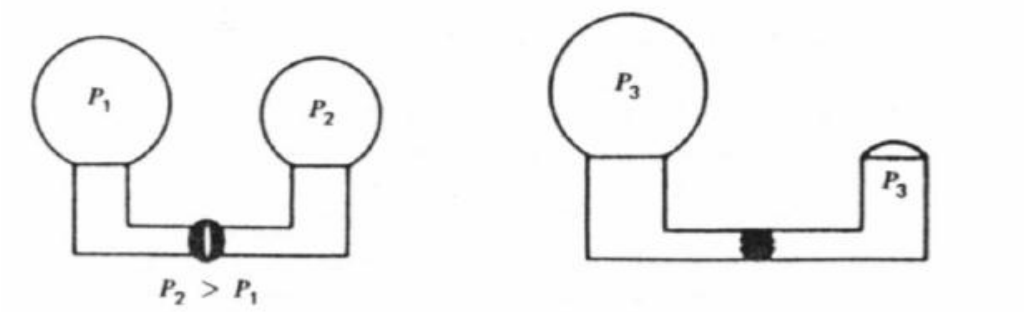
Physics of the Alveoli

The alveoli are physically like millions of small interconnected bubbles . They have a natural tendency to get smaller due the surface tension of a

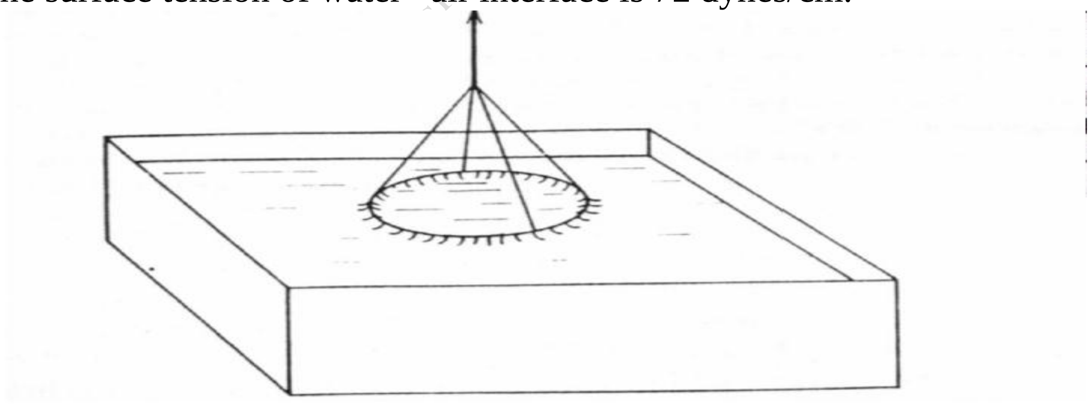
unique fluid lining .This lining called *surfactant* , it is necessary for the lung to function properly .
To understand the physics of alveoli we have to understand the physics of bubbles. According to *Laplace's law* , the pressure inside a bubble is inversely proportional to the radius and directly proportional to the surface tension .

Laplace's law   P=4S/R

surfactant:
The compliance of the lungs is made greater by the presence of surfactant in the alveoli. This substance acts like a detergent and reduce the surface tension of the water in the alveoli.
Ex.: The pressure inside a soap bubble depends on its radius (fig.4).
(a) when the valve between two bubbles is closed , the pressure is greater in small bubble .
(b) when the valve is opened , the smaller bubble empties into the larger , leaving a spherical cap with the same radius as the new large bubble .

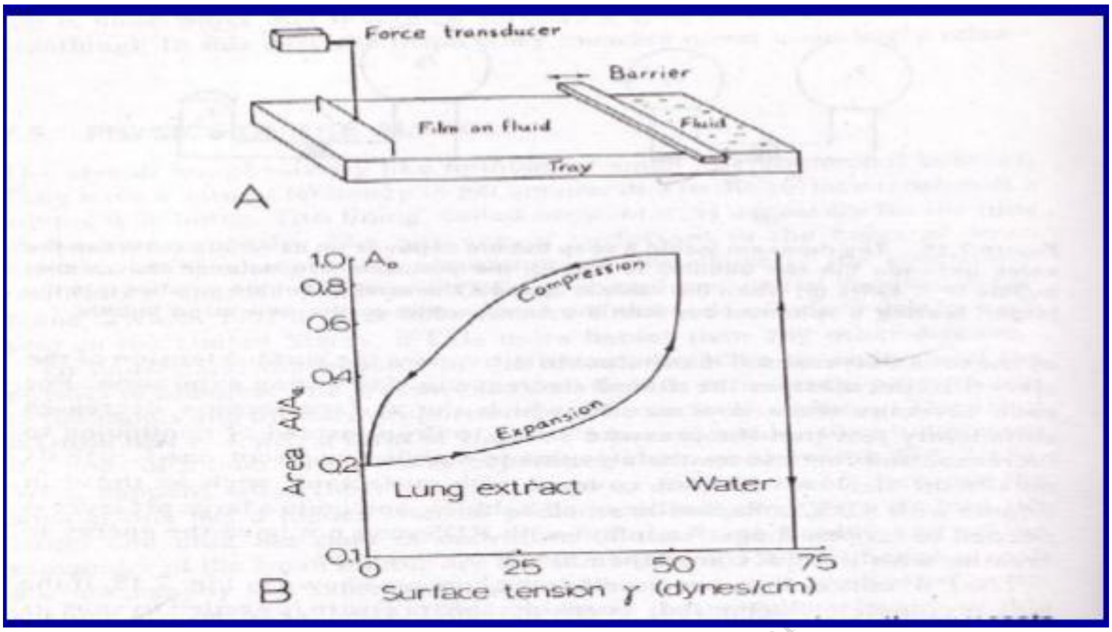


The surface tension of a fluid can be found by measuring how much force is necessary to pull a loop of a wire from a clean liquid surface (figure5). The surface tension of water –air interface is 72 dynes/cm.



The surface tension of the surfactant that lines the alveoli of healthy individuals plays a major role in lung function .The surface tension of the surfactant is not constant , as shown in figure (6) .The surfactant acts like a detergent and reduces the surface tension of the water in the alveoli .

Figure (6) Graph of surface tension of a lung extract containing surfactant . Note the large decrease in surface tension as the area decreases and the different curve obtained as the area increases . The vertical line at 70 dynes/ cm shows that the surface tension of water is constant with changes in area. This graph (figure6) .shows that the surface tension of the alveoli is a function of area.



Elasticity of lungs

The lungs and chest wall are elastic structures. The combined elasticity may be measured by relaxing the respiratory muscles, and then by how much the volume increases , when the pressure in the lungs increased.

$$\textbf{Elasticity} = \Delta P/\Delta v$$

ΔP = is the change in pressure
ΔV = is the change in volume

In respiratory mechanics it is usually to consider elasticity , but its reciprocal .

Compliance: is the change in the volume produced by a small change in pressure.

$$\textbf{Compliance} = \Delta v/\Delta p \quad \text{(Liters/cm of water)}$$

……Compliance in normal range is 0.18- 0.26 Liter/cm H_2O

The Breathing Mechanism

Breathing is normally under unconscious control . The physiological control of breathing depends on many factors , but the respiratory center of the brain exerts primary control .

If a lung were removed from the chest all the air would be squeezed from it and it would collapse to about one third of its size much as a balloon collapses when air is let out of it .The lungs can be thought of as millions of small balloons , all trying to collapse . The lungs do not normally

collapse because they are in an airtight container – the chest . As the diaphragm and rib cage move the lungs stay in contact with them .
Two forces keep the lungs from collapsing:

1. Surface tension between the lungs and the chest wall .
2. Air pressure inside the lungs .

If the lungs overcame the surface tension forces and pulled away from the chest wall a vacuum would be created since air can not reach the intrathoraic space .Since the air inside the lungs is at atmospheric pressure (10^5 N/m²) ,it would push the lungs back in contact with the chest wall . There is normally a negative pressure of 5 to 10 mm Hg in the intrapleural space . Various muscles are involved in breathing . Normally most breathing is done by contracting the diaphragm muscles . These pull the diaphragm down expanding the lungs .When we inspire ,we pull the diaphragm down as shown in figure (7) .

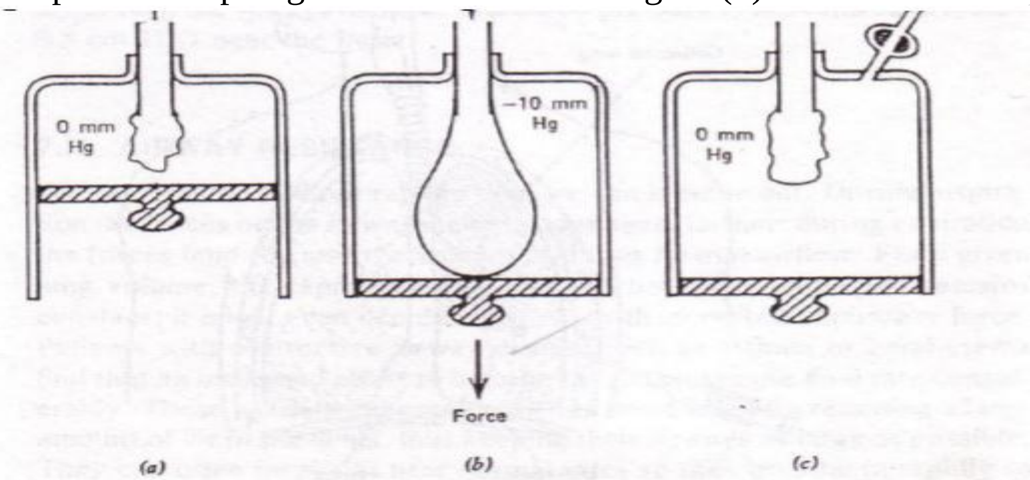


Figure 7 A simple model of the mechanisms of breathing (a) during expiration, (b) during inspiration, and (c) during pneumothorax.

This produces a slight negative pressure in the lungs and air flows in , when we expire ,we relax the diaphragm muscles , the elastic forces in the lungs cause the diaphragm to return to its neutral position , and air flows out of the lungs without any active muscular effort .
Since both the lungs and chest wall are elastic , we can represent them with springs ,figure(8) .Under normal conditions they are coupled together “the lung” springs are stretched and “chest” springs are compressed .

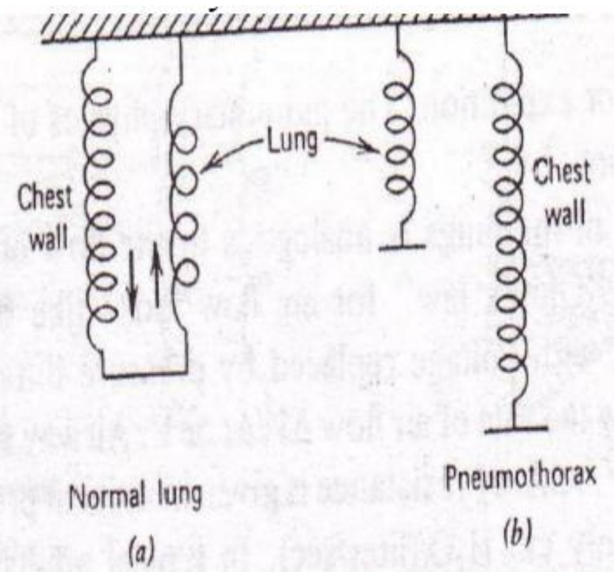


Figure (a) A spring model for the lungs. The arrows show the direction of the spring forces. Normally the lung and chest wall are coupled together. (b) During a severe pneumothorax, the springs go to their relaxed positions—the chest enlarges and the lung collapses.

During a *pneumothorax* , the lungs and chest are independent and the springs representing them go to their relaxed positions as indicated in figure (8b) . the lungs collapses ,and the chest wall enlarges .

The intrathoracic space is not always at negative pressure . If you close your wind pipe and forcefully try to expire , the intrathoracic pressure can become quite high . This is called a *Valsalva manenver* .

Airways Resistance

We can breath in more rapidly than we can breath out . During inspiration the forces on the airways tend to open them further; during expiration the forces tend to close the airways and thus restrict air flow .

The flow of air in the lungs is analogous to the flow of current in an electrical circuit . "*Ohm's law*" for air flow looks like ohms law for electrical circuit , with voltage replaced by pressure difference ΔP and current replaced by the rate of airflow Δv/Δt or V .

Airway resistance R_g is the ratio of Δ P to V.

$$\mathbf{R_g = \Delta P/V} \quad (\text{cm } H_2O/\text{ Liter/sec})$$

The flow rate of air flow is $V = \Delta v/\Delta t$

R_g depends on the dimensions of the tube and the *viscosity* of the gas $\boldsymbol{\eta}$.

The time constant of lungs is related to the airway resistance R_g and the compliance C .

Time constant for the lung $=R_gC$

This is analogous to the time constant RC or capacitor C to discharge through a resistance R in an electrical circuit .

The time constant of the lung is complicated since many parts of the lung are interconnected . If one part of the lung has a larger time constant than other parts , it will not get its share of the air and that part of the lung will be poorly ventilated.

Osmosis:

If we have two salts solutions of different concentrations separated by a membrane permeable to water not to salt , it is found that in time the solution on the two side will have the same strength . These due to the passage of water from the weak salt solution to the stronger . Such phenomena is known ***Osmotic Pressure*** as osmosis .

Is the force under which a solvent moves from a solution of a lower solute concentration to a solution of higher solute concentration .When these solution are separated by a selectively permeable membrane .

$$PV = nRT$$

Where **P** is the osmotic pressure

V is the volume

n is the number of mole

R is the universal gas constant = 8.3 J/mole

T is the absolute temperature

The osmotic pressure is proportional to the concentration of the solute ,
Which means inversely proportional to the volume of the solution .
It is also proportional to the absolute temperature .

Lung Diseases:

1. Disorder of low compliance:

-*Fibrosis*: scarring of connective tissue framework cause by many disease occupational hazards (welders miners) and ionizing radiation

1. Lung stiffens→ reduced compliance
2. Alveolar membrane thickens→O_2 cannot diffuse

-*RDS* (respiratory distress syndrome) : absence of surfactant→ reduced compliance.

2. Obstructive diseases:

-*Emphysema:*

1. Alveolar walls destroyed (due to smoking)
2. Lung flabby (i.e. increased compliance) →chest expands (barrel-chested) →hard to blow out, airway collapses when exhale

-*Asthma*: airway narrowing

1. Incidence on the rise: leading cause of hospitalization in children
2. Due to sensitive airway (allergic reaction)
3. Excess mucus secretion, bronchospasm (constriction of smooth lining airways) .