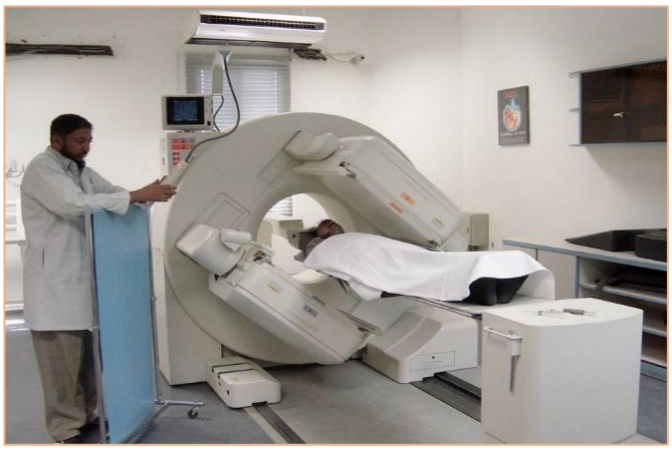
For 2nd grad Faculty of Science
(Biotechnology program)
2023

BIOPHYSICS



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Physics of the Cardiovascular System

The cells of the body act like individual engines. In order for them to function they must have: -

1. Fuel from our food to supply energy.
2. O_2 from the air we breathe to combine with the food to release energy.
3. A way to dispose of the by-products of the combustion (mostly CO_2, H_2O, and heat).

Since the body has many billions of cells an elaborate transportation system is needed to deliver the fuel and O_2 to the cells and remove the by-products. The blood performs this important body function. Blood represents about **7%** of the body mass or about 4.5 kg (~ 4.4 liters) in a 64 kg person. The blood, blood vessels, and heart make up the cardiovascular system (CVS).

Major components of the cardiovascular system

The heart is basically a double pump; it provides the force needed to circulate the blood through the two major circulatory systems: -

1. The pulmonary circulation in the lungs.

2. The systemic circulation in the rest of the body.

The blood in a normal individual circulates through one system before being pumped by the other section of the heart to the second system.

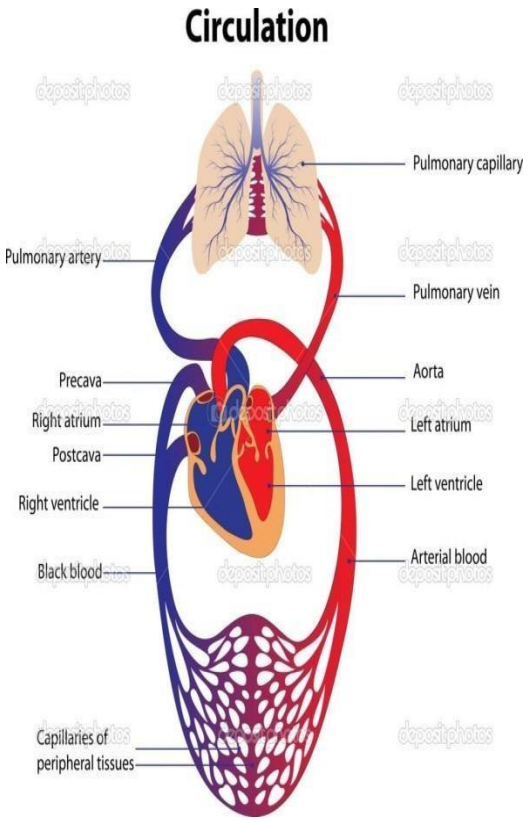
Circulation

Let us start with the blood in the left side of the heart and follow its circulation through one *complete* ***loop.***

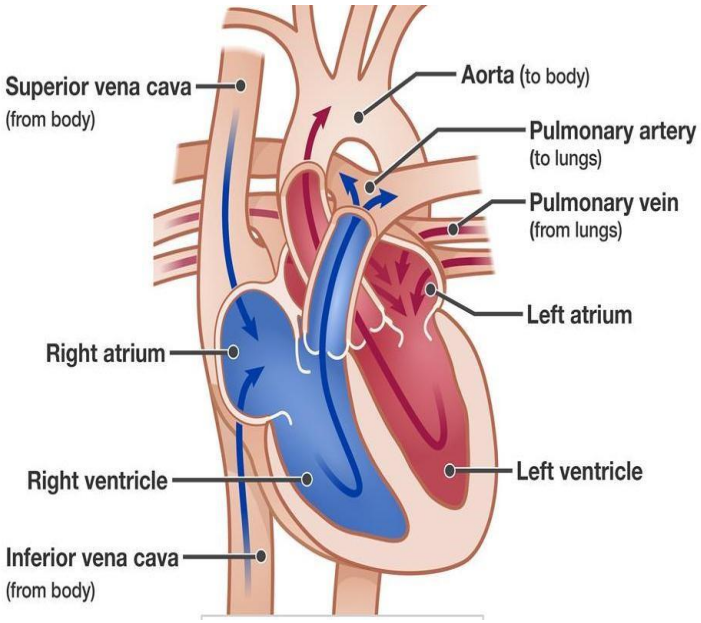
- The blood is pumped by the contraction of the heart muscles from the left ventricle at a pressure of about 125 mm Hg into a system of arteries that subdivided into

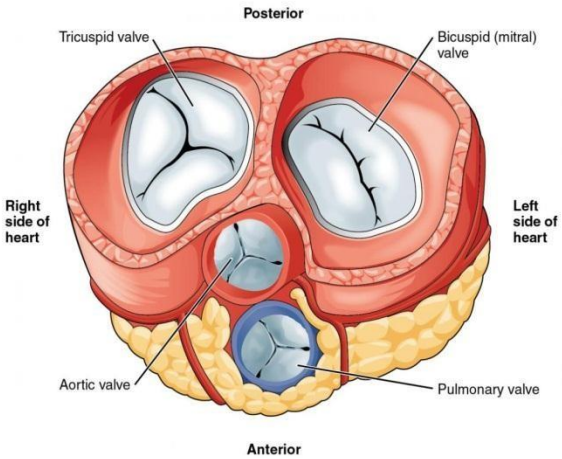
smaller and smaller arteries (arterioles) and finally into a very fine meshwork of vessels called the capillary bed.

- During the few seconds it is in the capillary bed the blood supplies O_2 to the cells and picks up CO_2 from the cells.
- After passing through the capillary bed the blood collects in small veins (venules) that gradually combine into larger and larger veins before it enters the right side of the heart via two main veins-the superior vena cava and the inferior vena cava.
- The returning blood is momentarily stored in the reservoir (the right atrium). And during a weak contraction (5-6 mm Hg) the blood flows into the right ventricular.
- On the next ventricular contraction this blood is pumped at a pressure of about 25 mm Hg via the pulmonary arteries to the capillary system in the lungs, where it receives more O_2 and where some of the CO_2 diffuses into the air in the lungs to be exhaled.
- The freshly oxygenated blood then travels via the main veins from the lungs into the left reservoir of the heart (left atrium); during the weak atrial contraction (7-8 mmHg) the blood flows into the left ventricle.
- On the next ventricular contraction this blood is again pumped from the left side of the heart into the general circulation.



The heart has a system of valves that, if functioning properly, permit the blood to flow only in the correct direction. If these valves become diseased and do not open or close properly the pumping of the blood becomes inefficient.





The blood volume is not uniformly divided between the pulmonary and systemic circulation, but it is: -

Blood Circulation 100/100					
Systemic Circulation 80/100			Pulmonary Circulation 20/100		
Arteries 15/100	Capillaries 10/100	Veins 75/100	Arteries 46.5/100	Capillaries 7/100	Veins 46.5/100

Q) Calculate the mass of blood in all circulation of a person his body mass is 80kg.

Mass of Blood 80 × 7/100 = 5.6 kg					
Mass of Blood in Systemic Circulation **5.6 × 80/100 = 4.48 kg**			**Mass of Blood in Pulmonary Circulation** **5.6 × 20/100 = 1.12 kg**		
Arteries	Capillaries	Veins	Arteries	Capillaries	Veins
4.48 × 15/100 = 0.672 kg	4.48 × 10/100 = 0.448 kg	4.48 × 75/100 = 3.360 kg	1.12 × 46.5/100 = 0.521 kg	1.12 × 7/100 = 0.078 kg	1.12 × 46.5/100 = 0.521 kg

Q) The mass of the pulmonary blood of a person is 1.5 kg, find: -

1) The mass of this person.

2) The mass of his systemic blood.

Pulmonary Mass = Blood Mass x 20/100

1.5 = Blood Mass x 20/100

Blood Mass = 7.5 kg

1)The mass of this person: -

Blood Mass = Body Mass x 7/100

7.5 = Body Mass x 7/100

Body Mass = 107 kg

2)The mass of his systemic blood: -

Systemic Mass = Blood Mass x 80/100

Systemic Mass = 7.5 x 80/100 ======== Systemic Mass = 6 kg

To the eye blood appears to be a red liquid slightly thicker than water. When examined by various physical techniques it is found to consist of several different components. The red color is caused by the red blood cells (erythrocytes). A nearly clear fluid called blood plasma accounts for the other 55%. The combination of red blood cells and plasma causes blood to have flow properties different from those of a fluid like water.

Beside red blood cells and plasma, there are some important blood components, such as the white blood cells (leukocytes), present in small amounts. The blood also contains platelets. Platelets are involved in the clotting function of blood.

The functions of the blood

1. Red blood cells carry oxygen from the lungs to the tissues and carbon dioxide from the tissues to the lungs.
2. Blood plasma transports antibodies, which protect the body from infection, carries food substances absorbed from the intestines and takes waste products to the kidneys for excretion. It also transports hormones, secreted by endocrine glands, to their sites of action.

3. Clotting factors circulating in the plasma prevent blood loss whenever blood vessels are damaged or broken.
4. Blood also regulates the water content of tissue cells.
5. Blood buffers, chemicals within the blood, maintain the correct acidity of body fluids.
6. Enzymes may be transported by blood plasma, which also distributes the heat produced by metabolism.

O_2 and CO_2 exchange in the capillary system

Oxygen and carbon dioxide also diffuse through tissue. The most probable distance *D* that a molecule will travel after *N* collisions with other molecules with an average distance λ between collisions is: -

$$D = \sqrt{N}$$

In tissue the density of the molecules is about **1000 times** greater than in air; therefore, λ is much longer in air than in tissue.

A typical value for λ in water, which can serve as a model for tissue, is about 10^{-11}m, and a molecule makes about 10^{12} collisions/sec. Thus after 1sec in water the most probable diffusion distance is about 10^{-5}m or about a factor of 10^{3} less than in air.

$$D = \sqrt{N}$$

$$= 10^{-11}\sqrt{10^{12}} = 10^{-11} \times 10^{6} = 10^{-5}\, m$$

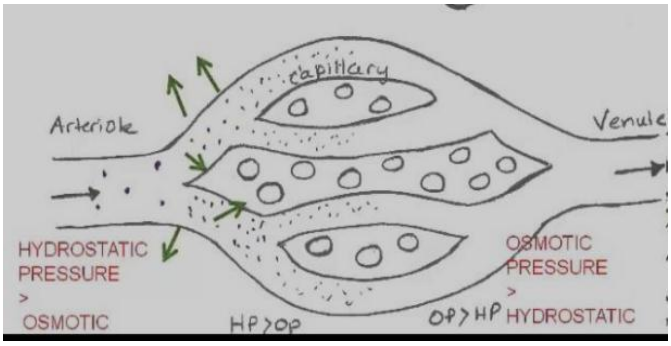
This very short diffusion distance is the primary reason that the capillaries in tissue must be very close together.

Not all capillaries are carrying blood at any one time. In resting muscle only 2 to 5% of the capillaries are functional.

Starling's law of capillary describes the flow of fluids into and out of the capillaries.

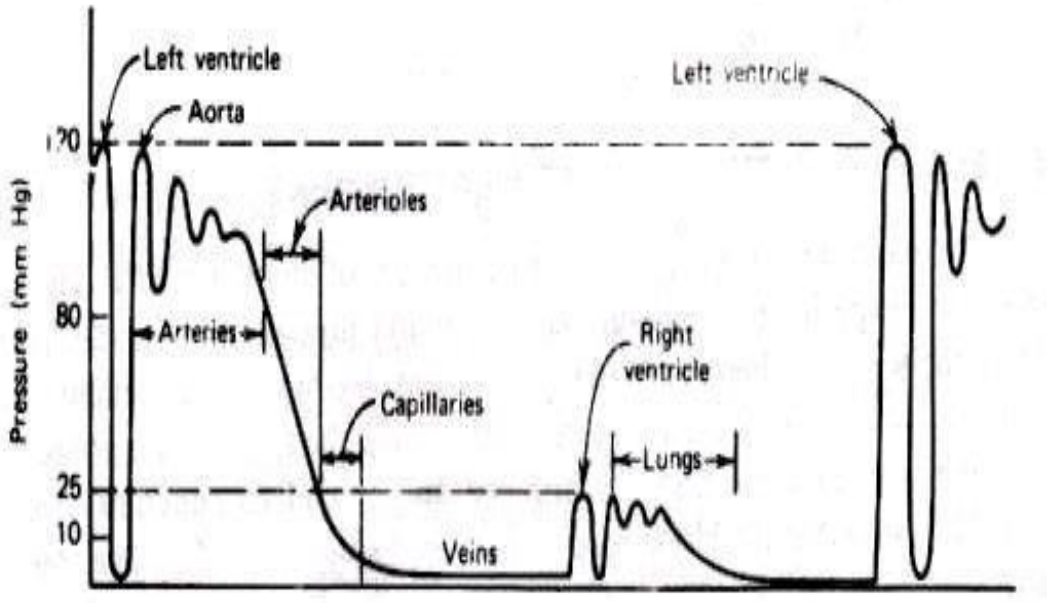
Fluid movement through the capillary wall is the result of two pressures: -

1. The hydrostatic pressure ρ across the capillary wall forcing fluids out of the capillary.
2. The osmotic pressure π bringing fluids in.



The heart

In a typical adult each contraction of the heart muscles forces about 80 ml (about **one third** of a cup) of blood through the lungs from the right ventricle and a similar volume to the systemic circulation from the left ventricle. In the process the heart does work.



The pressures in the two pumps of the heart are not the same. In the pulmonary system the pressure is quite low because of the low resistance of the blood vessels in the lungs.

The maximum pressure (systole), typically about 25 mmHg, is about **one-fifth** of that in the systemic circulation. In order to circulate the blood through the much larger systemic network the left side of the heart must produce pressures that are typically

about 120 mmHg at the peak (systole) of each cardiac cycle. During the resting phase (diastole) of the cardiac cycle the pressure is typically about 80 mmHg.

The muscle driving the left ventricle is about three times thicker than that of the right ventricle. In addition, the circular shape of the left ventricle is more efficient for producing high pressure than the elliptical shape of the right ventricle.

The work done W by a pump working at a constant pressure P is equal to the product of the pressure and the volume pumped ΔV, or

$$\mathbf{W=P\Delta V}$$

We can estimate the physical work done by the heart by multiplying its average pressure by the volume of blood that is pumped.

Actually the pumping action takes place in less than one-third of the cardiac cycle and the heart muscle rests for over two-thirds of the cycle.

Q) The heart rate of a person is 120 pulse/min; calculate the action time and the resting time of heart muscle.

120 pulse/1min = 120 pulse/60sec

2 pulse/1sec = 1pulse/0.5sec

1pulse = 1/3 contraction + 2/3 relaxation

0.5 ×1/3 = 0.17sec (the time of contraction)

0.5 ×2/3 = 0.33sec (the time of relaxation)

Q) Person has a systolic pressure 150 mmHg, diastolic pressure 100 mmHg, heart rate 90/min. Calculate the work done and the efficiency of the lower left half of the heart if the energy consume is 6 Watt.

Work done = PΔV

P average = (systolic + diastolic) /2

P average = (150+100) / 2

P average = 125 mmHg , 1 mmHg = 1330 dyne/cm^2

125 mmHg = 166250 dyne/cm^2

ΔV = amount of blood in each beat/sec × number of beat/sec

ΔV = 80ml/beat/sec x (90 beats/min)/(60sec/min)

ΔV = 120 cm^3

$$W = P\Delta V$$

Work = 166250 dyne/cm^2 x 120 cm^3

Work = 19950000 dyne.cm , 1 erg = 1 dyne.cm

Work = 19950000 erg , 1 erg = 10^{-7} Joule

Work = 1.995 Joule

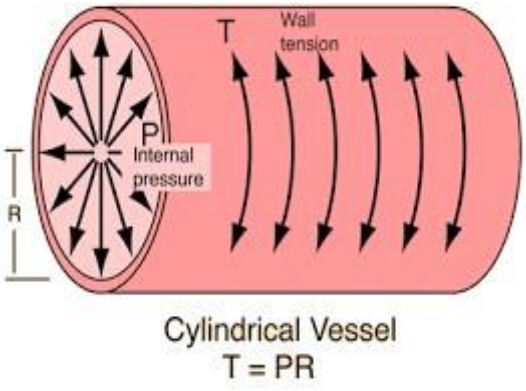
Efficiency = (Work done/Energy consume) ×100% Efficiency

= (1.995/6) ×100% = 33.25 %

Pressure across the blood vessel wall (Transmural Pressure)

The greatest pressure drop in the cardiovascular system occurs in the region of the arterioles and capillaries.

In order to understand why they do not burst we must discuss the law of Laplace, which tells us how the tension in the wall of a tube is related to the radius of the tube and the pressure inside the tube.



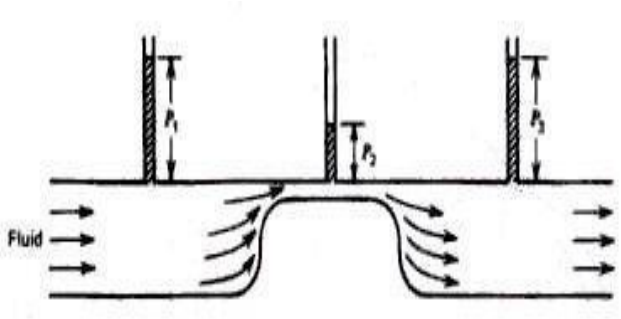
Consider a long tube of radius *R* carrying blood at pressure *P*. We can calculate the tension *T* in the wall (*T*=*RP*).

Bernoulli's principle applied to the cardiovascular system

Whenever there is a rapid flow of a fluid such as air or water, the pressure is reduced at the edge of the rapidly moving fluid.

Bernoulli's principle is based on the law of conservation of energy. Pressure in a fluid is a form of potential energy PE since it has the ability to perform useful work. In a moving fluid there is kinetic energy KE due to the motion. This kinetic energy can be expressed as energy per unit volume such as ergs per cubic centimeter.

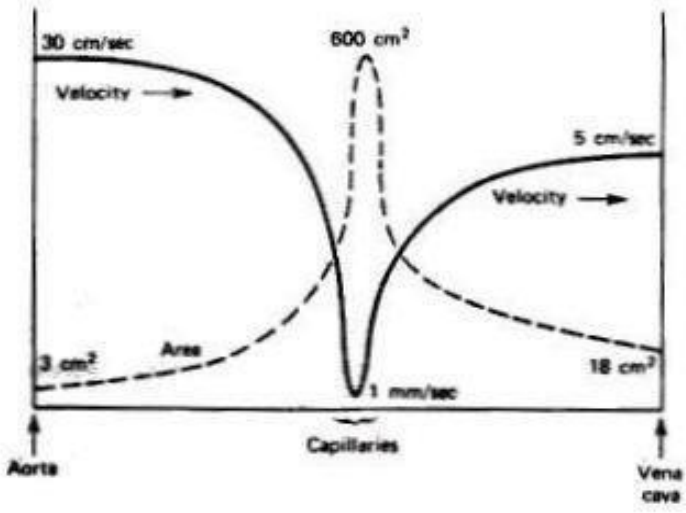
If fluid is flowing through the frictionless tube, the velocity increases in the narrow section and the increased kinetic energy KE of the fluid is obtained by a reduction of the potential energy PE of the pressure in the tube.



As the velocity reduces again on the far side of the restriction the kinetic energy is converted back into potential energy and the pressure increases again as indicated on the manometers.

How fast does your blood flow?

As the blood goes from the aorta into the smaller arteries and arterioles with greater total cross-sectional areas the velocity of the blood decreases much as the velocity of a river decreases at a wide portion.



Notice that the blood velocity is related in an inverse way to the total cross-sectional area of the vessels carrying the blood. The velocity equals the flow rate divided by the cross-sectional area. The average velocity in the aorta is about 30 cm/sec; that in a capillary is only about 1 mm/sec. It is in the capillaries that the exchange of O_2 and CO_2 takes place, and this low velocity allows time for diffusion of the gases to occur.

Blood Viscosity

You are undoubtedly aware of the characteristic of a liquid called viscosity (η). The viscosity of water is about 10^{-3} Pa s at 20°C [where 1 Pas = 1 N s/m^2 = 1 kg/(m s) in the SI system]. The viscosity of blood is typically $3x10^{-3}$ to $4x10^{-3}$ Pa s but depends on the percentage of red blood cells in the blood.

Blood Flow

Poiseuille's law states that the flow through a given tube depends on the pressure difference from one end to the other (P_A-P_B), the length L of the tube, the radius R of the tube, and the viscosity η of the fluid. When all of these variables are put together with a constant to keep the units working correctly we get Poiseuille's equation: -

$$Flow\ rate\ =\ P_A\ -\ P_B\ (\frac{\pi}{8})(\frac{1}{\eta})(\frac{R^4}{L})$$

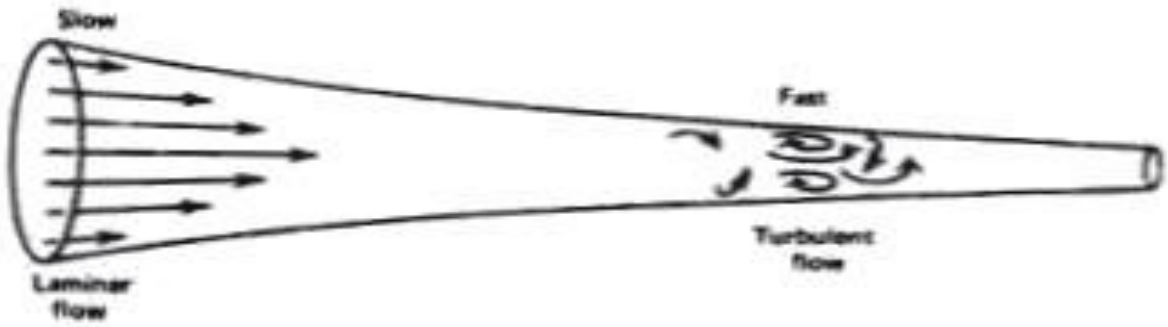
In SI units the flow rate will be in cubic meters per second if P_A-P_B is in Newtons per square meter, η is in Pa s, and R and L are in meters.

Blood flow-laminar and turbulent

You have probably seen both a slow, smooth, quietly flowing river and a rapid, turbulent, noisy river.

- The first type of river is analogous to the laminar or streamline flow that is present in most blood vessels.
- The second is similar to the turbulent flow found at a few places in the circulatory system, *for example*, where the blood is flowing rapidly past the heart valves.

An important characteristic of laminar flow is that it is silent. If all blood flow were laminar, information could not be obtained from the heart with a stethoscope. The heart sounds heard with a stethoscope are caused by turbulent flow. During a blood pressure measurement, the constriction produced by the pressure cuff on the arm produces turbulent flow and the resulting vibrations can be detected a stethoscope on the brachial artery.



If you gradually increase the velocity of a V_c fluid flowing in a tube by reducing the radius of the tube, it will reach a critical velocity V_c when laminar flow changes into turbulent flow.

The critical velocity will be lower if there are restrictions or obstructions in the tube. Osborne Reynolds determined that the critical velocity is proportional to the viscosity η of the fluid and is inversely proportional to the density ρ of the fluid and the radius R of the tube, $V_c = K\eta/\rho R$.

The constant of proportionality K is called the Reynold's number, and it is approximately equal to 1000 for many fluids, including blood, flowing in long straight tubes of constant diameter. If there are bends or obstructions the Reynold's number becomes much smaller.

Q) Find the kinetic energy (KE) of 2 gm of blood leaving aorta of radius 1.2 cm.

$$KE = \frac{1}{2}mv^2$$

$$v_c = \frac{K\eta_{blood}}{\rho R}$$

$$= \frac{1000 \times 3.5 \times 10^{-3}}{1.04 \times 10^3 \times 1.2 \times 10^{-2}} = 0.28\, m/sec$$

$$KE = \frac{1}{2} \times 0.002 \times (.28)^2 = 8 \times 10^{-5}\, Joule$$

Heart sounds

The heart sounds heard with a stethoscope are caused by vibrations originating in the heart and the major vessels. The opening and closing of the heart valves contribute greatly to the heart sounds; turbulent flow occurs at these times and the vibrations produced are often in the audible range.

The amount and quality of the sound heard depend on the design of the stethoscope as well as on its pressure on the chest, its location, the orientation of the body, and the phase of the breathing cycle.

The physics of some cardiovascular diseases

Because of the many physical aspects of the cardiovascular system, heart diseases often have a physical component. Many of these diseases, *for example*, increase the workload of the heart or reduce its ability to work at a normal rate.

The work done by the heart is roughly the tension of the heart muscle times how long it acts. Anything that increases the muscle tension or how long it acts will increase the workload of the heart. *For example*, high blood pressure (hypertension) causes the muscle tension to increase in proportion to the pressure. A fast heart rate (tachycardia) increases the workload since the amount of time the heart muscles spend contracting increases.

To reduce the workload of the heart, bed rest and O_2 therapy are prescribed. Giving O_2 increases the O_2 in the blood so that less blood must be pumped to the tissues.

Man-made device that has helped heart patients is the artificial heart valve.

Heart valve defects are of two types: -

- **Stenosis**: - the valve does not open wide enough. In stenosis the work of the heart is increased because a large amount of work is done against the obstruction of the narrow opening, and the blood supply to the general circulation is reduced.
- **Insufficiency**: - the valve does not close well enough. In insufficiency some of the pumped blood flows back into the heart so that the volume of the circulated blood is reduced.

The Physics of Lungs and Breathing

Function of Lungs & Breathing:

1- Exchange of **O_2** & **CO_2** between the blood and air.

2- Keeping pH (acidity) of the blood constant. "When we do work pH increase "**$CO_2 + H_2O \rightarrow H_2CO_3$**"

3- Heat exchange between the body and atmosphere.

4- Fluid balance of the body by warming and moistening the air we breathe.

5- Voice production.

6- Removing the dust particles stuck to the moist lining of various air ways.

Breathing Rate:

1- We breathe ≈ 6 liters of air per min.

2- Men breath ≈ 12 times / min at rest.

3- Women breath ≈ 20 times / min at rest.

4- Infants breath ≈ 60 times / min at rest.

* The air we inspired is ≈ 80 % N_2, 20 % O_2

Expired air is ≈ 80 % N_2, 16 % O_2 & 9 % Co_2

The air ways in the body

1- **The noise**: Air is warmed, filtered and moistened by the moist surface and hairs, which trap particles and dirt.

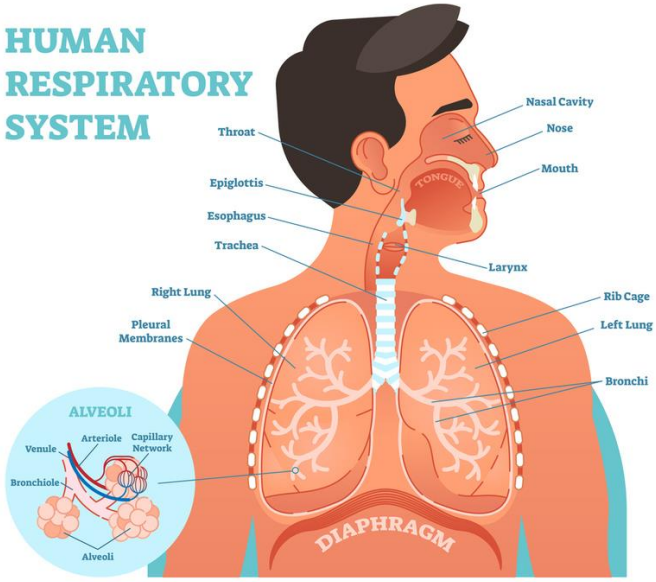
2- **The trachea**: A windpipe that the air passes through goes to a lung.

3- **The bronchi**: Two divisions from the trachea .Each bronchus go to a lung.

4- **Bronchioles:** Each bronchus divides and red vides 15 times into smaller branches call bronchioles.

5- **Alveoli:** Air sacs 30 million at birth, 300 million at age 8 years and more, beyond this age the number of stays relatively constant but the alveoli increase in diameter.

Alveoli which are like small interconnected bubbles are about 0.2 mm in diameter and half a wall's only 0.4 micrometer thick in, the expand and control during breathing. They surrounded by blood, so that $\mathbf{O_2}$ can diffuse from the alveolus into the red blood cells and CO_2 can diffuse from the blood into the air in the alveoli.



There are two processes involved O2 and CO2 exchange in the lung:

1- **Perfusion** (P): getting the blood to the pulmonary capillaries.

2- **Ventilation** (V): getting the air to the alveolar surface.

There are three P- V. areas in the lung:

1- **Areas with good. P. good V.** which accounts over 90% of the total volume of normal lung.

2- **Areas with poor P. good V.** where a blood flow to part of a lung is blood by a clot.

3- **Areas with good P. poor V**. where air passages in the lungs are obstructed as in pneumonia.

Partial Pressures of O_2 and CO_2:

The behavior of the gases (Air exchange by diffusion) obeys to the Dalton's Law of partial pressures:

(The total pressure of different gases is the sum of the pressures of each would exert when it alone occupied the contained)

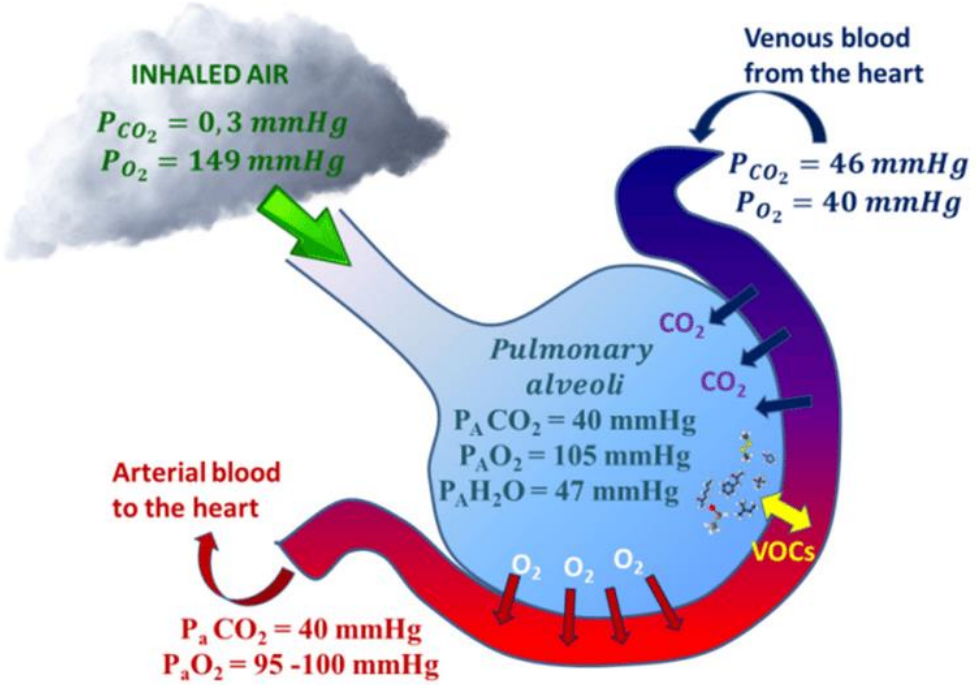
Partial Pressure = % (gas)* (atmospheric – partial pressure of water vapor)

In the lung at 37C° & 100 % relative humidity, the partial pressure of water vapor = 47 mmHg, atmospheric pressure.= 760 mmHg

The alveolar airs contain 14 % O_2 & 5.6 % Co_2.

PO_2 = 14/ 100 *(760mmhg – 47 mm hg) ≈ 100 mm hg.

PCO_2 = 5.6/ 100* (760mm hg – 47 mm hg) ≈ 40mm hg.



Henry Law: It's stated the solubility of gases in liquids "The amount of gas which a liquid will dissolve directly proportional to the partial pressure of the gas".

O_2 → is not very soluble in blood or water.

→ It diffuses faster than a molecule of Co_2 because of its smaller mass & higher PO_2.

Co_2 → Is larger than that O_2 molecule, which actually slow the rate of diffusion, because of low PCO_2 & larger mass.

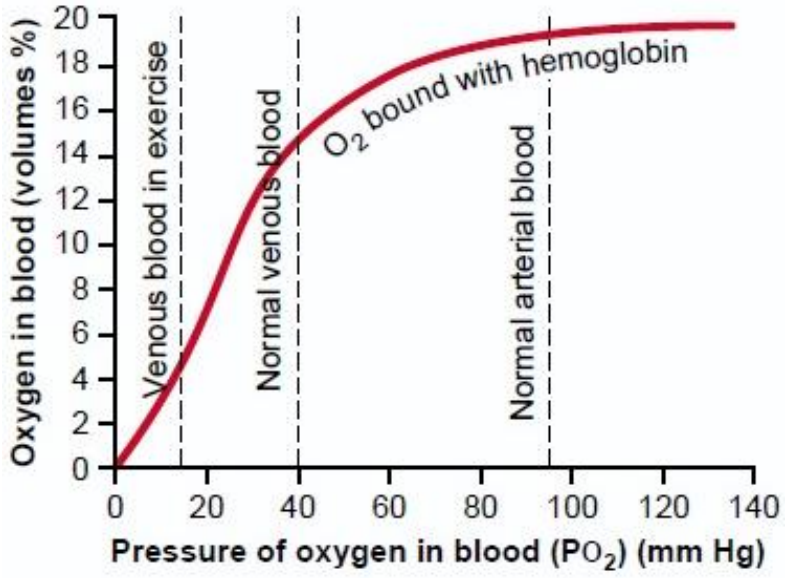
On other hand, the CO_2 is ≈ 25 times more soluble in liquids than the O_2, so that the net effect is that the CO_2 diffuses about 20 times more rapidly in aqueous liquids than does O_2 .

1 lit of blood can hold ≈ 2.5cm^3 of O_2 (100 mmHg) and ≈ 15 cm^3 of CO_2 (40 mmHg).

Combination of O_2 with Hb:

Because of the low solubility of O_2 in the blood most of the O_2 combine with Hb in the blood red cells to be carried to the body cells.

The Hb leaving the lungs ≈ 97% saturate with O_2 at PO_2 = 100 mmHg. O_2 dissociate from Hb and diffuse into the cells because of their low PO_2 environment.



The dissociation of O_2 from Hb is dependent on:

1- PCO_2 in the cells;

2- The pH ;

3- The temperature ;

4- PO_2 of the tissue (cells).

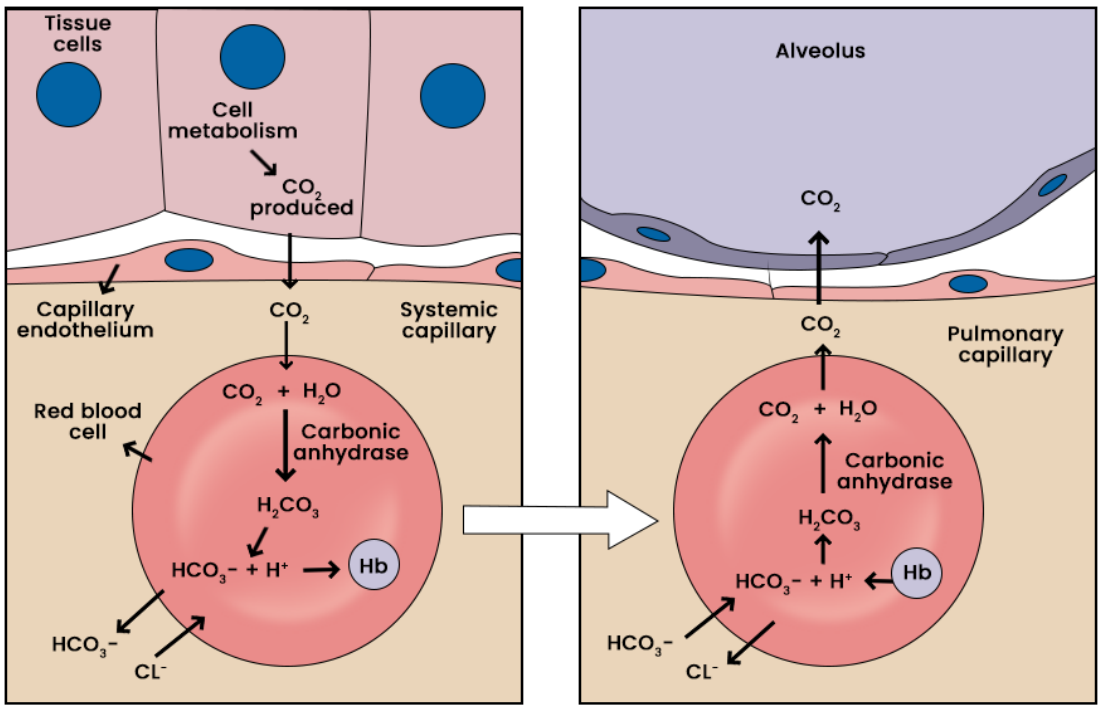
* Under resting condition the venous blood return to the heart with 75% of its load of O_2 because it is not needed by the tissues:

*** During exercise, PCO_2, pH, and temperature are all increased which permit Hb to give most of its O_2 .**

* In addition, the body can increase the blood flow three times, working muscles, which results in O_2 supply of 10 times more than they consume at rest.

CO_2 Transporting

Most of CO_2 remains in the blood after it have left the lungs (PCO_2 = 40 mmHg). The CO_2 levels in the blood are maintained fairly constant by the breathing rate.



- **The ratio of CO_2 output to O_2 in take is called Respiratory exchange ratio (Respiratory quotient) R<1.**
- **At each normal breath ≈ 500 cm^3 of fresh air (PO_2 150mm Hg) mixed with ≈ 2000 cm^3 of stale air in the lung to result in alveolar air with PO_2 ≈ 100 mm Hg.**

CO Poisoning (Carbon monoxide):

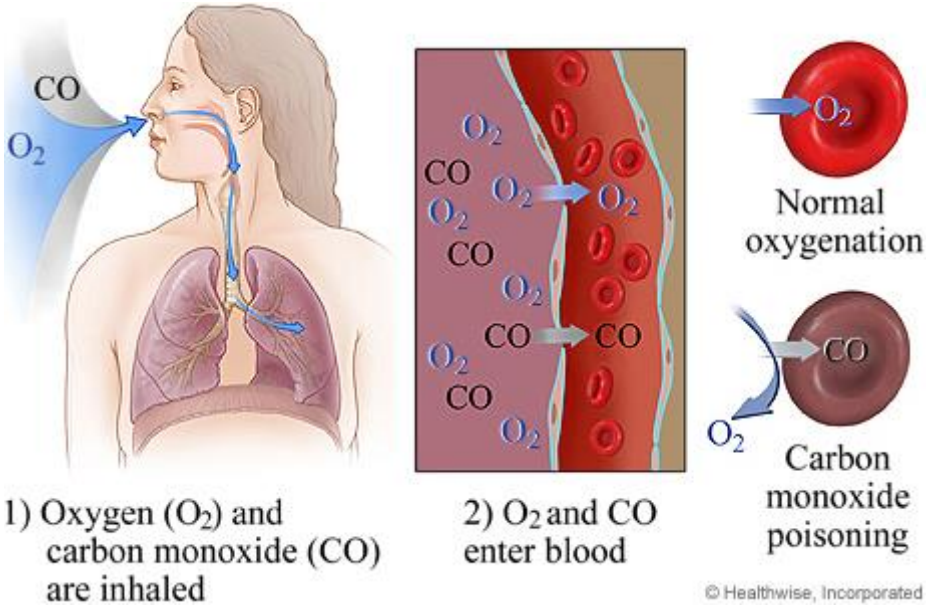
1- CO molecules attach with Hb nearly 250 times more tightly than O_2.

2- Do not easily dissociate in the tissue.

3- Occupy places in Hb normally used to transport O_2.

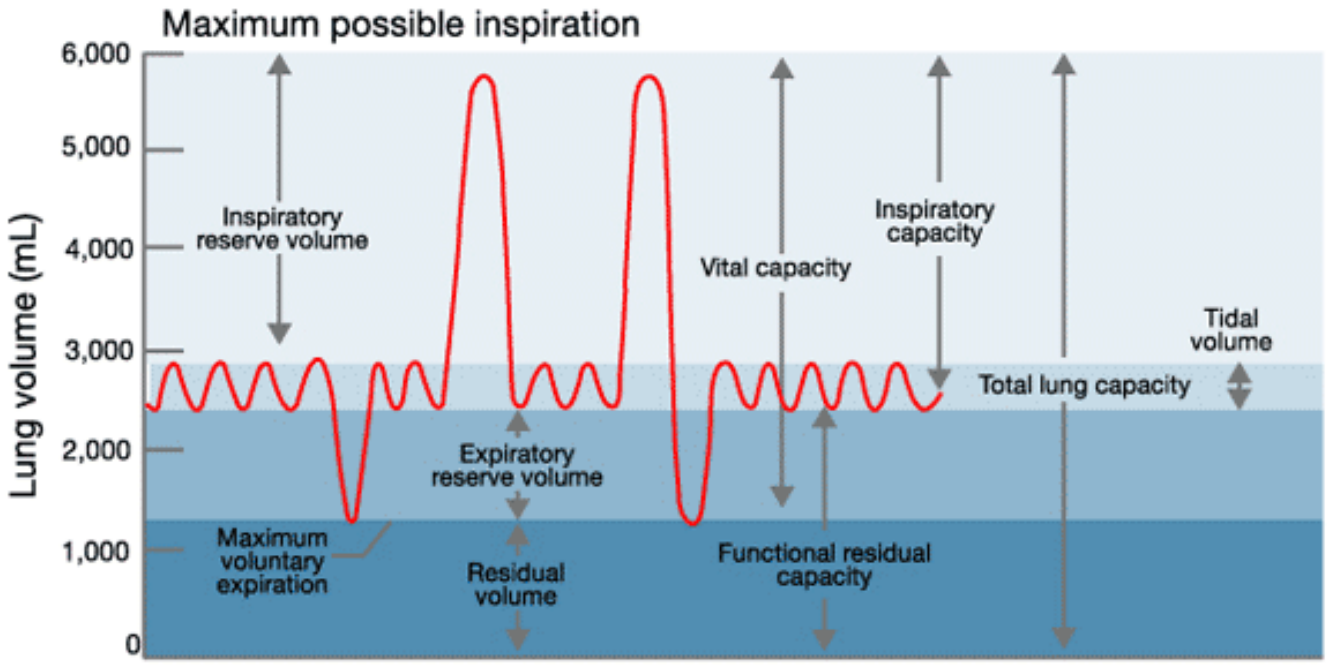
4- CO inhibits the release of O_2 from Hb

So even a small amount CO can seriously reduce the O_2 to the tissue.



Measurement of lung volume

The lung has various volumes and capacities. The volume of the lung versus time (i.e. the air flow) can be measured by the spirometer which record it on a graph. These volumes and capacities can be summarized as follows (which is shown by the graph):



1. ***Tidal volume at rest:***

It is the volume of air inhaled with each breath during normal breathing at rest (~ 500 cm^3). During heavy exercise the tidal volume is considerably large.

2. ***Inspiratory reserve volume:***

It is the additional air taken at the end of inspiration, which is possible with some effort to further fill the lungs with air.

3. ***Expiratory reserve volume:***

It is the additional expired air, which can be forced out of the lungs at the end of normal expiration.

4. ***Functional residual capacity (FRC):***

It is the air remaining in the lungs after a normal respiration where the stale air mixes with the fresh air of the next breath.

5. ***Vital capacity:***

The volume of air exhaled when the breath is as deeply as possible and then exhaled as much as possible.

6. *Residual volume:*

It is the amount of air stale in lungs after vital capacity, which is ~1lit for adult.

Dead Spaces:

There are spaces in respiratory system at which air does not provide O_2 to the body. They are:

500 cm^3 = 150 cm^3 (A.D. spaces) + 350 cm^3 (alveolar air)

Anatomic dead spaces:

Fresh air does not go directly to alveoli .It goes first through the conducting airway .Because there is no significant exchange of O_2 & CO_2 between gas & blood in the conducting air way ,the internal volume of airway is called **anatomic dead space**.

Physiological (alveolar) dead spaces: It is the unused alveolar volumes, in which alveolar capillaries are not perfuse with blood , and O_2 is not absorbed in the alveoli.

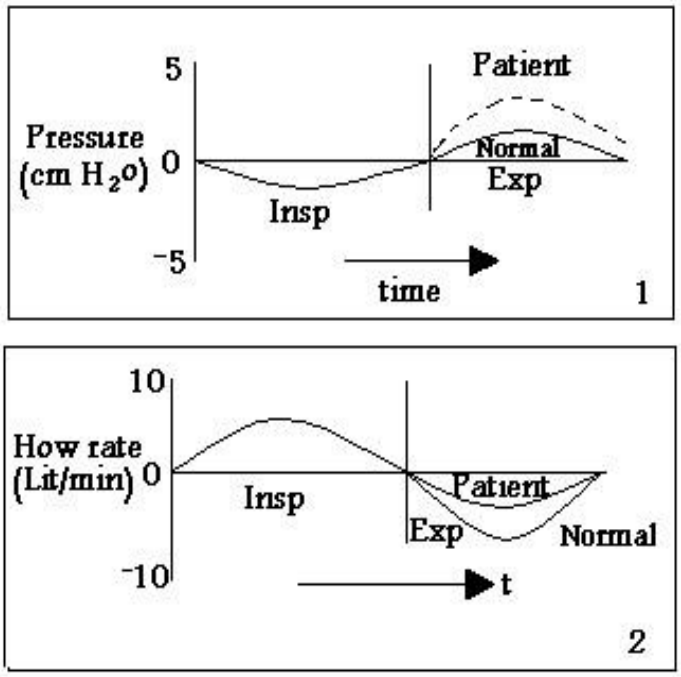
Airway diseases test:

- The maximum rate of expiration after a maximum inspiration is a useful test for obstructive airway diseases where the flow rate sometimes decreases with excessive expiratory effect. During the maximum expiration the out flow is rapid at first; the last 5% takes longer than the first 95%.
- A normal person can expire nearly 70% of his vital capacity in 0.5 sec., 85% at 1 sec., 94% in 2 sec., 97% in 3 sec.

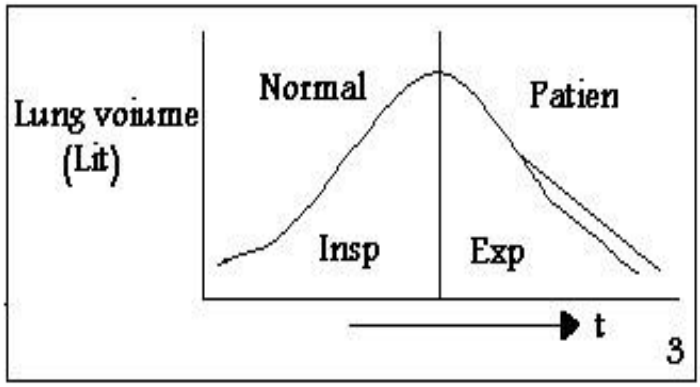
Pressure – airflow – Volume relationships in the lung

- The lungs of a healthy individual need small P to cause air to flow into or out of them ,which is few cms of H_2O as in fig(1)

- The increase pressure and decreased air flow for a patient with narrowed airway during expiration and increased airflow into or out of the normal lungs as in fig 1 and 2.

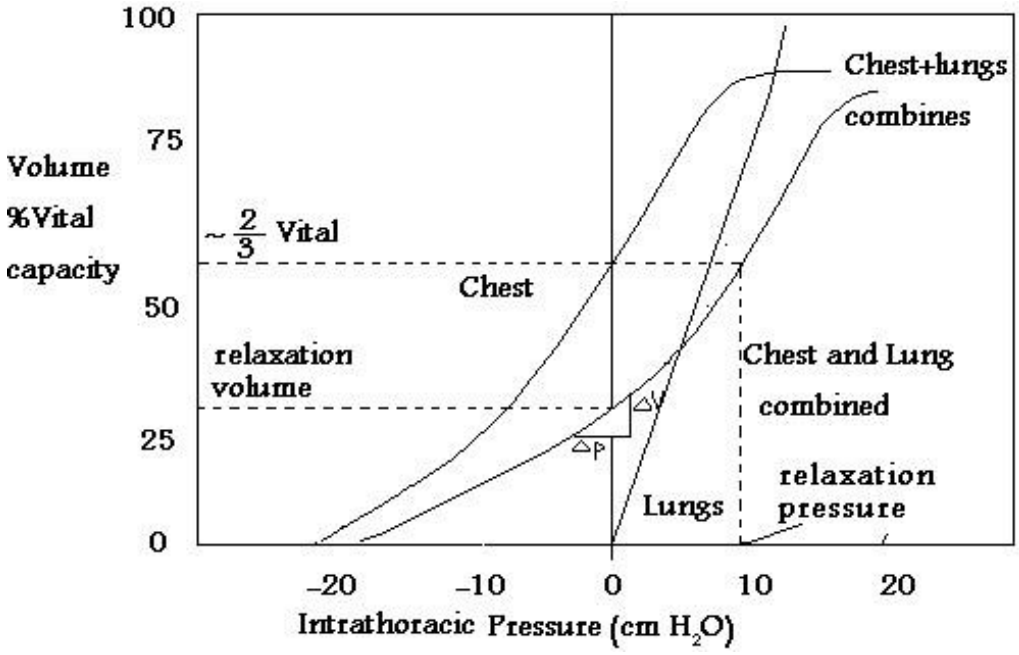


The lung volume during breathing cycle for a normal and for a patient with narrowed airways as in fig 3



The Pressure – Volume Curve:

The esophagus reflects the pressure between the lungs and chest wall (intrapleural or intrathoracic) the pressure in the esophagus "can be measured with a pressure gauge which in normally (-10 mmHg) due to the elasticity of the lungs.



From P.V. Curve:

1- If the chest wall (alone) ;i.e. without interaction with lung the volume =2/3 of total vital capacity at P = O The lung would collapse & have no air volume.

2- If the chest wall & lung together;

The volume = 30 % of vital capacity (come to Relaxation volume FRC) at P=O.

The volume = 60 % of vital capacity, the pressure = +10 cm .H_2O, This pressure is called Relaxation pressure & is produced by elastic properties of the lung.

Compliance: It is an important physical characteristic of the lungs:

(Is the change in the volume produced by a small change in pressure).

$$C = \frac{\Delta V}{\Delta P} = \frac{change\ in\ volume}{change\ in\ pressure} = \frac{Liter}{cm.H_2O}$$

***In normal adult, the range of compliance= 0.18 – 0.27 (lit / cm. H_2O)**

***A Stiff lung (fibro tic) has a small Δ V for large Δ P.**

$$C = \frac{Small\ \Delta V}{\text{Large } \Delta P} = Low\ compliance$$

*** A flabby lung has :**

$$C = \frac{Lagre\ \Delta V}{Small\ \Delta P} = Large\ compliance$$

a. Infants with respiratory distress syndrome have lungs with low compliance.

b. B. In some disease such as emphysema, the compliance increase.

Physics of the alveoli

- The alveoli are physically like millions of small interconnected sacs (like bubbles).The alveoli lining is an unique fluid called surfactants which is necessary for a lung to work properly, due to the surface tension (γ) of this fluid .
- The pressure inside the alveoli can be calculated due to (Laplase Law) (which is applied on bubble) p= 4 γ/r where r is the radius of alveolus.
- The surface tension of the surfactant is not constant because the surface area of the alveolus is variable during breathing.

Airway Resistance (Ra):

Depend on 1- The dimension of airway 2- The viscosity of gas

$$R_a = \frac{\Delta P}{f_r}$$

Where fr is the flow rate $= \frac{\Delta V}{\Delta t}$ for typical adult Ra= 3.3 cm.H_2O / (lit/sec)

Time Constant (Tc)

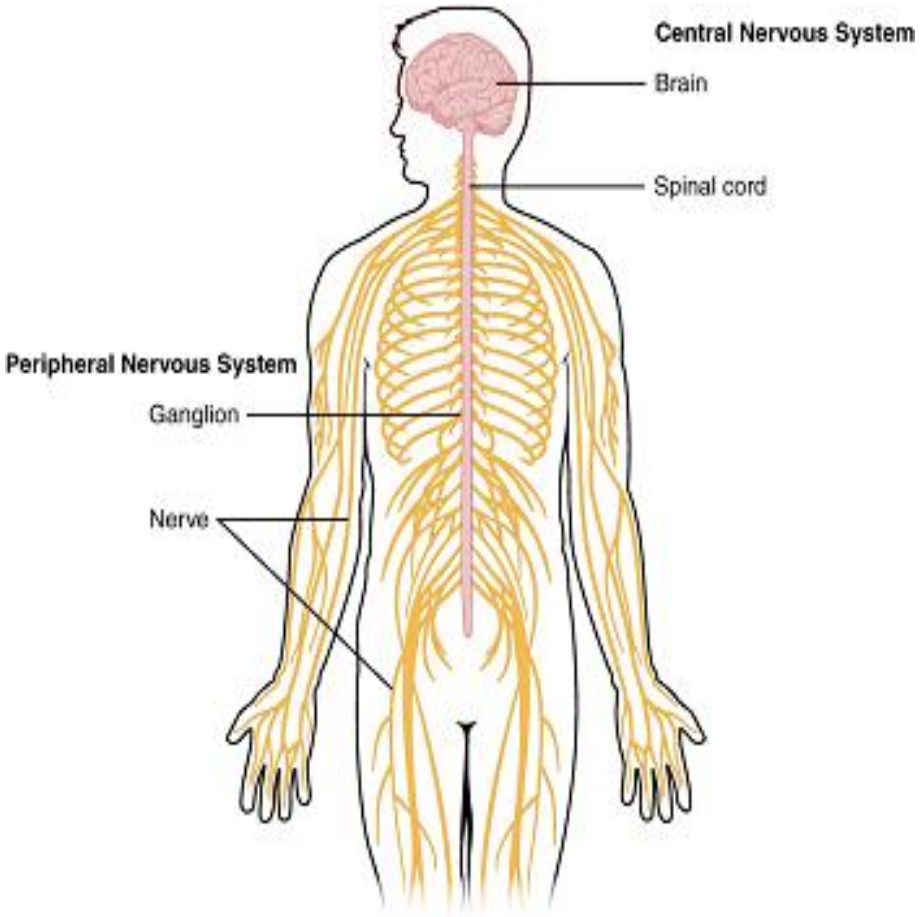
$$T_c = R_a C = \frac{\Delta P}{(\Delta V/\Delta t)} \times \frac{\Delta V}{\Delta P}\ (Sec)$$

Bioelectricity and human nervous system

The **nervous system** is the part of the human body that coordinates its actions and transmits signals to and from different parts of its body. Nervous tissue first arose in wormlike organisms about 550 to 600 million years ago. In vertebrate species it consists of two main parts:

- The central nervous system(CNS)
- The peripheral nervous system (PNS).

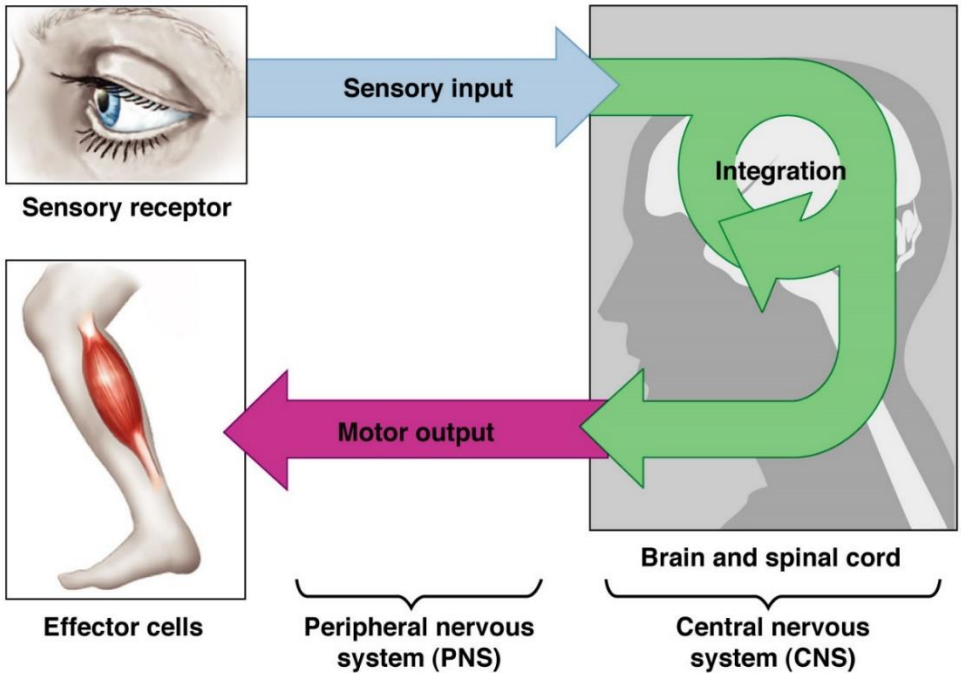
The CNS contains the brain and spinal cord. The PNS consists mainly of nerves, which are enclosed bundles of the long fibres or axons that connect the CNS to every other part of the body. Nerves that transmit signals from the brain are called *motor* or *efferent* nerves, while those nerves that transmit information from the body to the CNS are called *sensory* or *afferent*. Most nerves serve both functions and are called *mixed* nerves.



The Neuron

The neurons, which are the basic units of the nervous system, can be divided into three classes: sensory neurons, motor neurons, and interneurons.

- **The sensory neurons** receive stimuli from sensory organs that monitor the external and internal environment of the body. Depending on their specialized functions, the sensory neurons convey messages about factors such as heat, light, pressure, muscle tension, and odor to higher centers in the nervous system for processing.
- **The motor neurons** carry messages that control the muscle cells. These messages are based on information provided by the sensory neurons and by the central nervous system located in the brain.
- **The interneurons** transmit information between neurons.



Basic structure

A typical neuron consists of a **cell body (soma), dendrites, axon and synapse**.

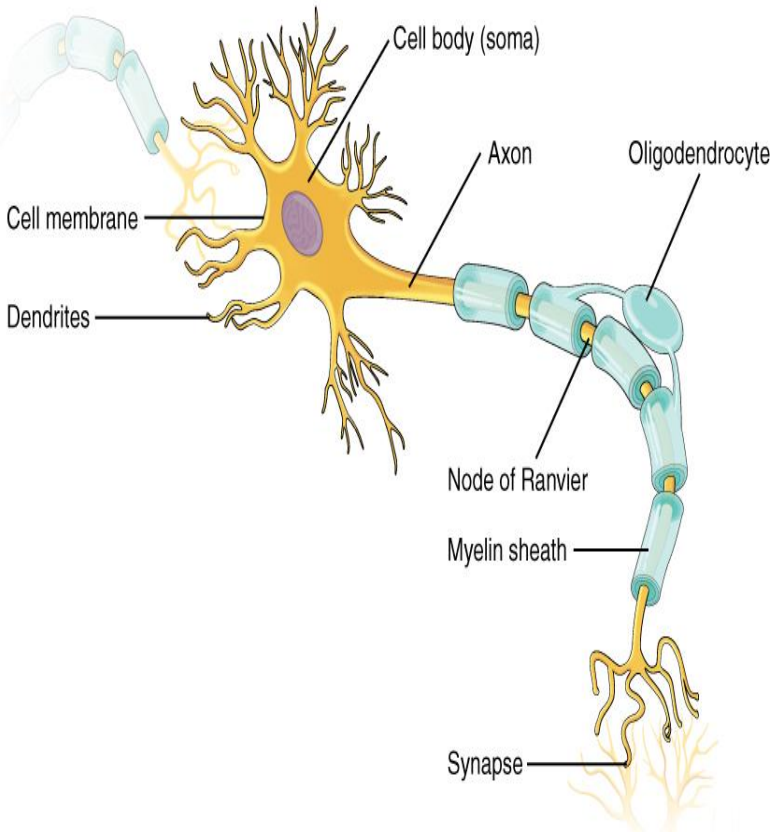
1- Dendrites are thin structures that arise from the cell body, often extending for hundreds of micrometers and branching multiple times, giving rise to a complex "dendritic tree".

2- **The axon**, which is an extension of the neuron cell, conducts the electrical impulses away from the cell body. Some axons are long indeed—in people, for example, the axons connecting the spine with the fingers and toes are more than a meter in length. Some of the axons are covered with a segmented sheath of fatty material called **myelin**. The segments are about 2mm long, separated by gaps called the **Nodes of Ranvier.**

Although each axon propagates its own signal independently, **many axons often share a common path within the body**. These axons are usually grouped into **nerve bundles**.

3- The cell body of a neuron frequently gives rise to multiple dendrites, but never to more than one axon, although the axon may branch hundreds of times before it terminates.

4- Synapses are functional connections between neurons, or between neurons and other types of cells.

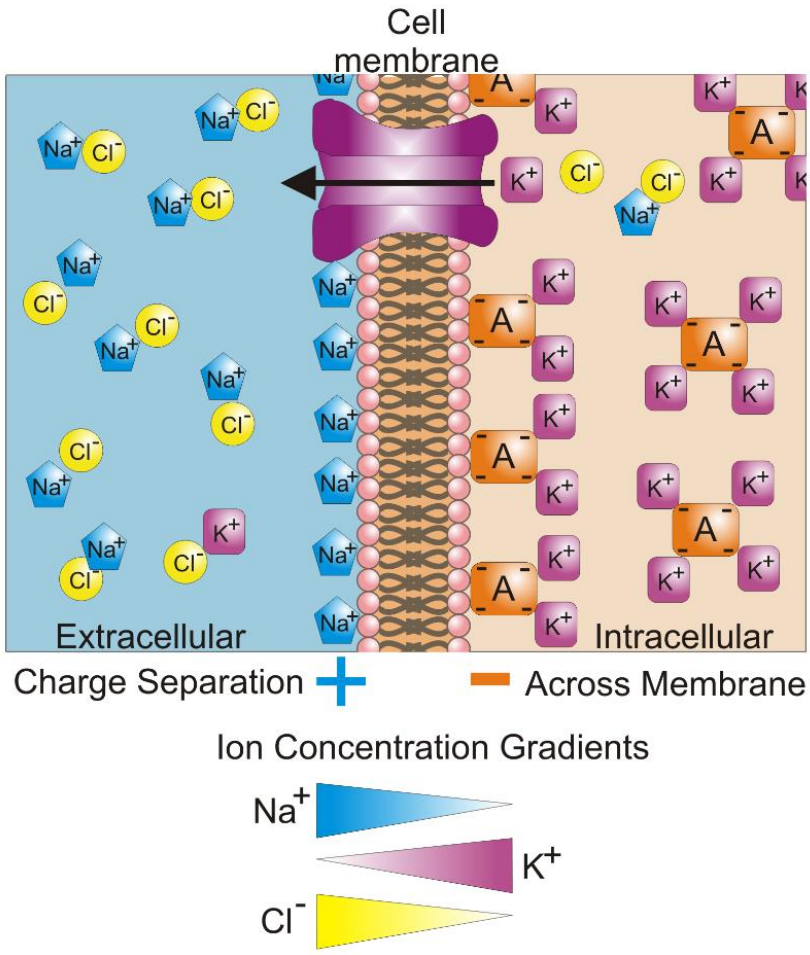


Electrical Potentials in the Axon

In the aqueous environment of the body, salt and various other molecules dissociate into positive and negative ions. As a result, body fluids are relatively good conductors of electricity. Still, these fluids are not nearly as conductive as metals; their resistivity

is about 100 million times greater than that of copper, for example. The inside of the axon is filled with an ionic fluid that is separated from the surrounding body fluid by a thin membrane.

The axon membrane, which is only about 50–100 ˚A thick, is a relatively good but not perfect **electrical insulator**. Therefore, some current can leak through it. The electrical resistivities of the internal and the external fluids are about the same, but their chemical compositions are substantially different. The external fluid is similar to sea water. Its ionic solutes are mostly **positive sodium ions** and **negative chlorine ions**.



Inside the axon, the positive ions are mostly potassium ions, and the negative ions are mostly large negatively charged organic molecules.

Because there is a large concentration of sodium ions outside the axon and a large concentration of potassium ions inside the axon, we may ask why the concentrations are not equalized by diffusion. In other words,

why don't the sodium ions leak into the axon and the potassium ions leak out of it?

The answer lies in the properties of the axon membrane.

In the resting condition, when the axon is not conducting an electrical pulse, the axon membrane is highly permeable to potassium and only slightly permeable to sodium ions. The membrane is impermeable to the large organic ions. Thus, while sodium ions cannot easily leak in, potassium ions can certainly leak out of the axon. However, as the potassium ions leak out of the axon, they leave behind the large negative ions, which cannot follow them through the membrane. **As a result, a negative potential is produced inside the axon with respect to the outside**. This negative potential, which has been measured to be about **-70mV**, holds back the outflow of potassium so that in equilibrium the concentration of ions is as we have stated. Some sodium ions do in fact leak into the axon, but they are continuously removed by a metabolic mechanism called the sodium pump.

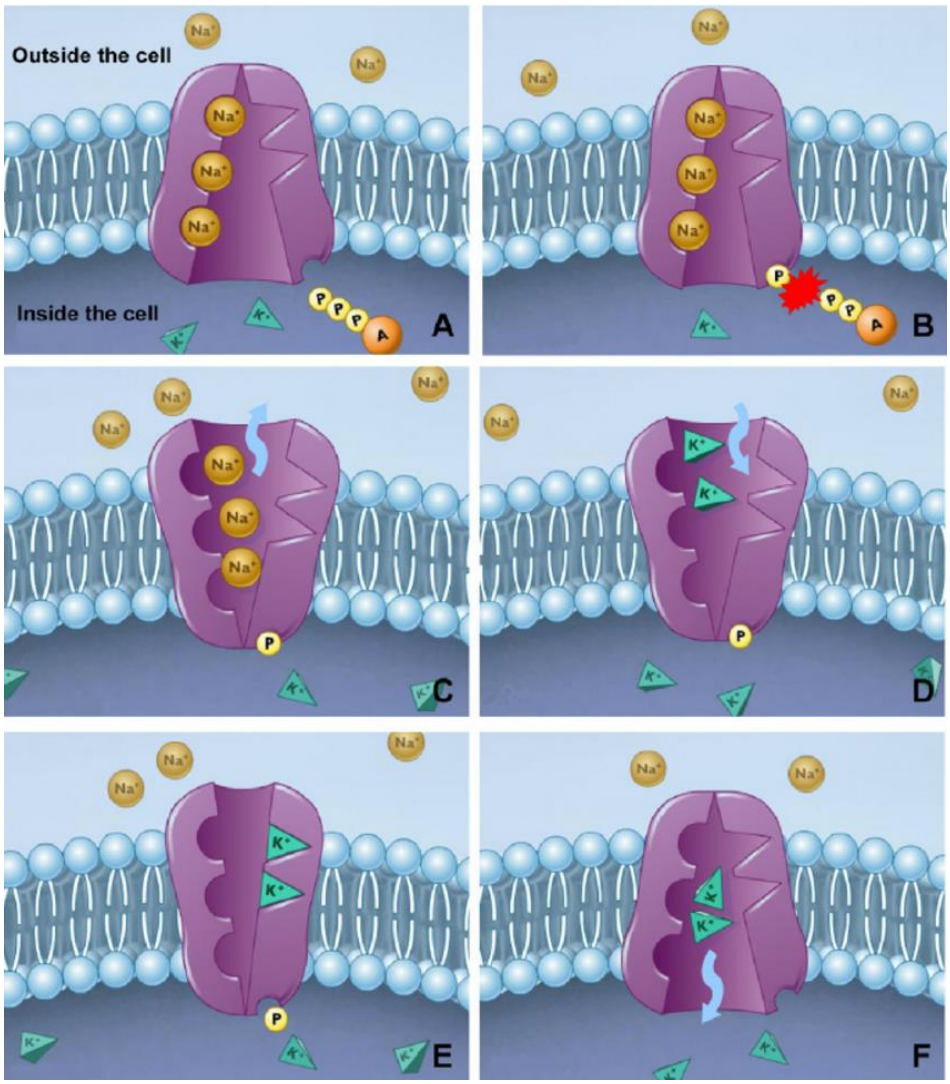
Sodium/ potassium pump mechanism

The sodium pump is a membrane protein that uses energy in the form of adenosine triphosphate (ATP) to perform active transport of sodium ions out of the cell in exchange for potassium ions into the cell. For every adenosine triphosphate molecule that the pump uses, **three sodium ions** are **exported**, while **two potassium** are **imported**; there is hence a net export of a single positive charge per pump cycle. For one complete cycle of the pump the mechanism is:

A. The pump, after binding ATP, binds 3 intracellular Na^+ ions
B. ATP is hydrolyzed, leading to phosphorylation of the pump at a highly conserved aspartate residue and subsequent release of ADP
C. A conformational change in the pump exposes the Na^+ ions to the outside. The phosphorylated form of the pump has a low affinity for Na^+ ions, so they are released

D. The pump binds 2 extracellular K^+ ions. This causes the dephosphorylation of the pump, reverting it to its previous conformational state, transporting the K^+ ions into the cell.

E. The unphosphorylated form of the pump has a higher affinity for Na^+ ions than K^+ ions, so the two bound K^+ ions are released. ATP binds, and the process starts again.



Action Potential

The functions of the nervous system—sensation, integration, and response—depend on the functions of the neurons underlying these pathways. To understand how neurons are able to communicate, it is necessary to describe the role of an excitable membrane

in generating these signals. The basis of this communication is **the action potential**, which demonstrates how changes in the membrane can constitute a signal.

The concentration of ions in extracellular and intracellular fluids is largely balanced, with a net neutral charge. However, a slight difference in charge occurs right at the membrane surface, both internally and externally. It is the difference in this very limited region that has all the power in neurons (and muscle cells) to generate electrical signals, including action potentials. Before these electrical signals can be described, the resting state of the membrane must be explained.

Resting membrane potential describes the steady state of the cell, which is a dynamic process that is balanced by ion leakage and ion pumping. **Without any outside influence, it will not change**.

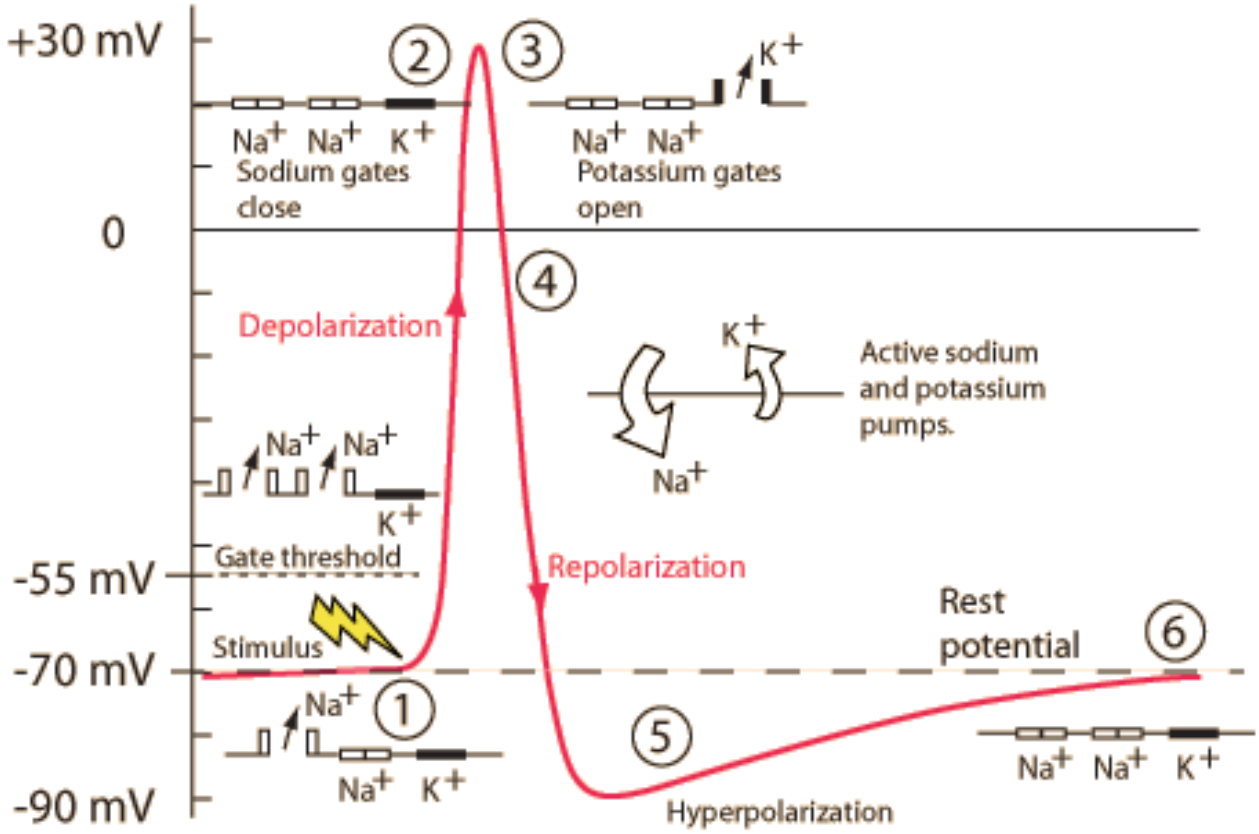
To get an electrical signal started, the membrane potential has to change. This starts with a channel opening for Na^+ in the membrane. Because the concentration of Na^+ is higher outside the cell than inside the cell by a factor of 10, ions will rush into the cell that are driven largely by the concentration gradient. Because sodium is a positively charged ion, it will change the relative voltage immediately inside the cell relative to immediately outside. The resting potential is the state of the membrane at a voltage of -70 mV, so the sodium cation entering the cell will cause it to become less negative. This is known as **depolarization**, meaning the membrane potential moves toward zero.

The concentration gradient for Na^+ is so strong that it will continue to enter the cell even after the membrane potential has become zero, so that the voltage immediately around the pore begins to become positive. The electrical gradient also plays a role, as negative proteins below the membrane attract the sodium ion. The membrane potential will reach +30 mV by the time sodium has entered the cell.

As the membrane potential reaches +30 mV, other voltage-gated channels are opening in the membrane. These channels are specific for the potassium ion. A concentration gradient acts on K^+, as well. As K^+ starts to leave the cell, taking a positive charge with

it, the membrane potential begins to move back toward its resting voltage. This is called **repolarization**, meaning that the membrane voltage moves back toward the -70 mV value of the resting membrane potential.

Repolarization returns the membrane potential to the -70 mV value that indicates the resting potential, but it actually overshoots that value. Potassium ions reach equilibrium when the membrane voltage is below -70 mV, so a period of **hyperpolarization** occurs while the K^+ channels are open. Those K^+ channels are slightly delayed in closing, accounting for this short overshoot.



The question is, now, what initiates the action potential?

The description above conveniently glosses over that point. But it is vital to understanding what is happening. The membrane potential will stay at the resting voltage until something changes. The description above just says that a Na^+ channel opens. Now, to say "a channel opens" does not mean that one individual

transmembrane protein changes. Instead, it means that one kind of channel opens. There are a few different types of channels that allow Na^+ to cross the membrane.

- **A mechanically gated channel opens** because of a physical distortion of the cell membrane. Many channels associated with the sense of touch (somatosensation) are mechanically gated. For example, as pressure is applied to the skin, these channels open and allow ions to enter the cell. Similar to this type of channel would be the channel that opens on the basis of temperature changes, as in testing the water in the shower.
- A **voltage-gated channel** is a channel that responds to changes in the electrical properties of the membrane in which it is embedded. Normally, the inner portion of the membrane is at a negative voltage. When that voltage becomes less negative, the channel begins to allow ions to cross the membrane
- A **leakage channel** is randomly gated, meaning that it opens and closes at random, hence the reference to leaking. There is no actual event that opens the channel; instead, it has an intrinsic rate of switching between the open and closed states. Leakage channels contribute to the resting transmembrane voltage of the excitable membrane.

Equivalent circuit of the cell membrane

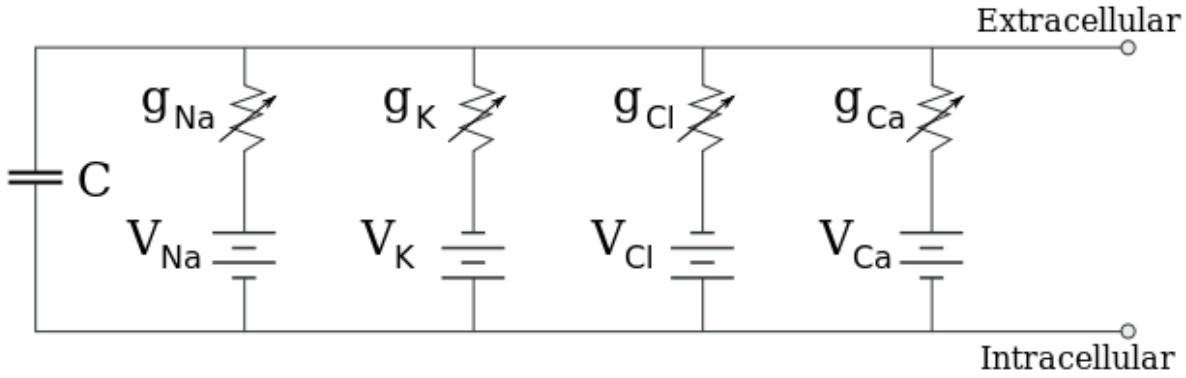
The Equivalent Circuit Model of the plasma membrane of excitable cells is an extremely useful model for understanding the ionic basis of membrane potentials. This applies equally to the resting membrane potential as well as the transient action potentials. There are 3 components to the model:

A capacitor: as indicated in the diagram, the plates of the capacitor correspond roughly to the inner and outer faces of the plasma membrane, which are 'formed' by the polar head groups of the constituent phospholipids that comprise the bilayer structure of the membrane.

Variable resistances: in keeping with current practice, these are actually labelled as variable conductances, g, rather than resistances.

Electromotive forces: these are represented in the model as batteries.

Note that each ion, in this case Na^+, K^+, and Cl^-, is represented by its own component of the circuit. Each of these consists of a variable conductance and an emf. Also note that all of these ion circuit components are in parallel with each other.



Physiological hazard of electricity

A voltage applied to a human body causes an electric current through the tissues, and although the relationship is non-linear, the greater the voltage, the greater the current. The threshold for perception varies with the supply frequency and with the path of the current but is about 0.1 mA to 1 mA for mains-frequency electricity, though a current as low as a microamp can be detected as an electro vibration effect under certain conditions. If the current is sufficiently high, it will cause muscle contraction, fibrillation of the heart, and tissue burns. The lack of any visible sign that a conductor is electrified makes electricity a particular hazard. The pain caused by an electric shock can be intense, leading electricity at times to be employed as a method of torture. Death caused by an electric shock is referred to as electrocution. Electrocution is still the means of judicial execution in some jurisdictions, though its use has become rarer in recent times.

Electrocardiography (ECG or EKG)

Definitions

Electrocardiography (ECG or EKG) is the process of recording the electrical activity of the heart over a period of time using electrodes placed on the skin. These electrodes detect the tiny electrical changes on the skin that arise from the heart muscle's electrophysiologic pattern of depolarizing and repolarizing during each heartbeat.

Electrocardiograph is a device used in the diagnosis and detection of heart abnormalities

Electrocardiogram is (cardiology) the visual output that an electrocardiograph produces.

Biological aspects

During each heartbeat, a healthy heart has an orderly progression of depolarization that starts with pacemaker cells in the sinoatrial node, spreads out through the atrium, passes through the atrioventricular node down into the bundle of His and into the Purkinje fibers, spreading down and to the left throughout the ventricles. This orderly pattern of depolarization gives rise to the characteristic ECG tracing. To the trained clinician, an ECG conveys a large amount of information about the structure of the heart and the function of its electrical conduction system. Among other things, an ECG can be used to measure the rate and rhythm of heartbeats, the size and position of the heart chambers, the presence of any damage to the heart's muscle cells or conduction system, the effects of cardiac drugs, and the function of implanted pacemakers.

Cardiac Conduction System

The Cardiac Conduction System consist of two main systems:

- Ordinary myocardium (atrial and ventricular)
- Specialized cardiac conduction system, which includes the following:
  - sinoatrial node;
  - anterior, middle, and posterior internodal tracts;
  - atrioventricular (AV) node;
  - bundle of His; right and left bundle branches;

- anterior-superior and posterior-inferior divisions of the left bundle;
- The Purkinje networks

From the standpoint of the electrocardiographer, the heart consists of three types of cells:

- **Pacemaker cells**—the normal electrical power source of the heart
- **Electrical conducting cells**—the hard wiring of the heart
- **Myocardial cells**—the contractile machinery of the heart.

The electrical events of the cardiac cycle:

The cardiac cycle is the sequence of events that occurs when the heart beats.

As the heart beats, it circulates blood through pulmonary and systemic circuits of the body.

There are two phases of the cardiac cycle:

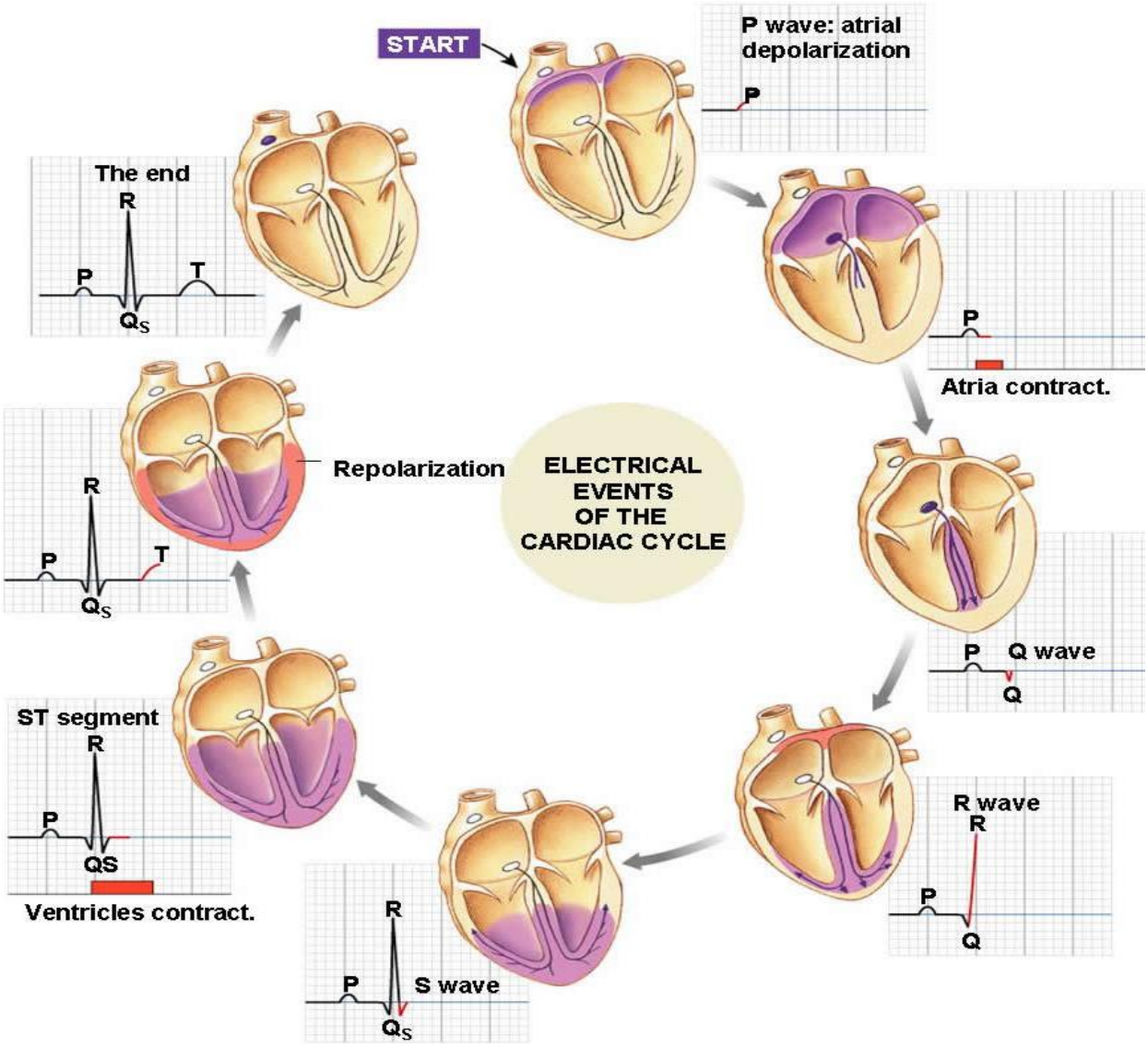
- ✓ **In the diastole phase,** the heart ventricles are relaxed and the heart fills with blood.
- ✓ **In the systole phase,** the ventricles contract and pump blood out of the heart and to arteries.

One cardiac cycle is completed when the heart chambers fill with blood and blood is then pumped out of the heart.

1. The sinoatrial (SA) node and the remainder of the conduction system are at rest.
2. The SA node initiates the action potential, which sweeps across the atria.
3. After reaching the atrioventricular node (AV), there is a delay of approximately 100 ms that allows the atria to complete pumping blood before the impulse is transmitted to the atrioventricular bundle.
4. Following the delay, the impulse travels through the atrioventricular bundle and bundle branches to the Purkinje fibers, and also reaches the right papillary muscle via the moderator band.
5. The impulse spreads to the contractile fibers of the ventricle.
6. Ventricular contraction begins.

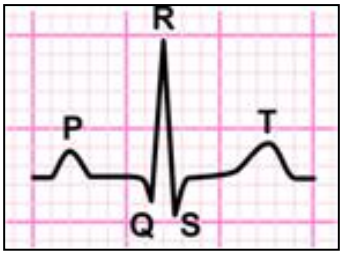
Electrocardiograph

- The fundamental component to electrocardiograph is the **Instrumentation amplifier**, which is responsible for taking the voltage difference between leads (see below) and amplifying the signal. ECG voltages measured across the body are on the order of hundreds of microvolts up to 1 millivolt (the small square on a standard ECG is 100 microvolts).

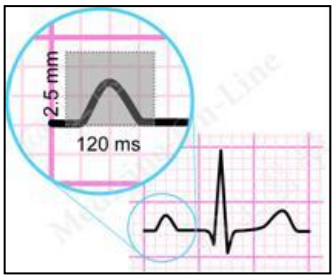


Electrocardiogram

Atrial and ventricular depolarization and repolarization are represented on the ECG as a series of waves: The P wave followed by the QRS complex and the T wave.

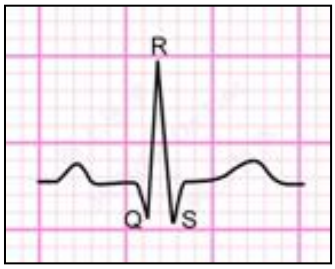


1- The P Wave:

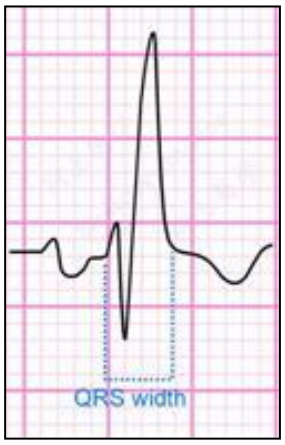


The first deflection is the P wave associated with right and left atrial depolarization. Wave of atrial repolarization is invisible because of low amplitude. Normal P wave is no more than 2.5 mm (two-and-a half1-mm-divisions) tall and less than 120 ms (three 1-mm-divisions) in width in any lead.

2- The QRS Complex

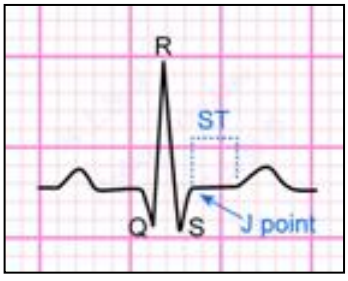


The second wave is the QRS complex. Typically, this complex has a series of 3 deflections that reflect the current associated with right and left ventricular depolarization. By convention the first deflection in the complex, if it is negative, is called a Q wave. The first positive deflection in the complex is called an R wave. A negative deflection after an R wave is called an S wave. A second positive deflection after the S wave, if there is one, is called the R' wave. Some QRS complexes do not have all three deflections. But irrespective of the number of waves present, they are all QRS complexes.



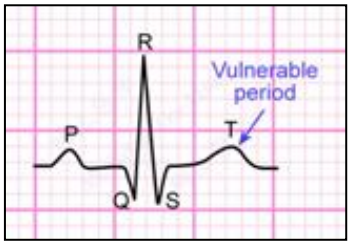
QRS duration is the width of that complex from beginning to end, irrespective of the number of deflections present. Normally it lasts no more than 120 ms (three 1-mm-divisions).

3- The ST Segment



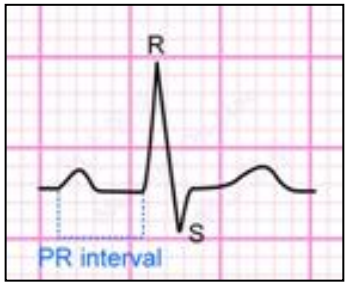
Following the QRS complex is the ST segment, extending from where the QRS ends (irrespective of what the last wave in the complex is) to where the T wave begins. The junction between the end of the QRS and the beginning of the ST segment is called the J point.

4- The T Wave



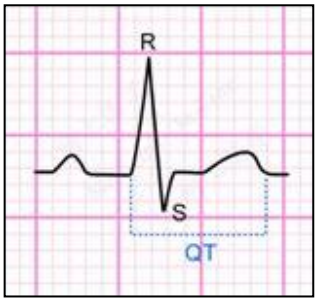
The T wave represents the current of rapid phase 3 ventricular repolarization (see diagram above). The polarity of this wave normally follows that of the main QRS deflection in any lead. The ventricles are electrically unstable during that period of repolarization extending from the peak of the T wave to its initial downslope. A stimulus (e.g. a run away heart beat called a premature beat) falling on this vulnerable period has the potential to precipitate ventricular fibrillation: the so call R-on-T phenomenon.

5- The PR Interval



The PR interval extends from the beginning of the P wave to the beginning of the QRS, whatever the first wave of this complex may be. This interval measures the time from the initial depolarization of the atria to the initial depolarization of the ventricles and reflects a physiological delay in AV conduction imposed by the AV node. Normal range is 120 – 200 ms (3 to 5 1-mm-divisions) and no longer.

6- The QT Interval



The QT interval is measured from the beginning of the QRS to the end of the T wave. It represents the time in which the ventricles depolarize and repolarize and is a measure of ventricular action potential (AP) duration.

ECG medical uses

The overall goal of performing electrocardiography is to obtain information about the structure and function of the heart. Medical uses for this information are varied and generally relate to having a need for knowledge of the structure and/or function. Some indications for performing electrocardiography include:

- Assess heart rhythm
- Diagnose poor blood flow to the heart muscle (ischemia)

- Diagnose a heart attack
- Diagnose abnormalities of your heart, such as heart chamber enlargement and abnormal electrical conduction

Electroencephalography (EEG)

Definitions

Electroencephalography (EEG) is the process of recording the electrical activity of the brain. During an EEG test, small electrodes like cup or disc type are placed on the scalp. They pick up the brain's electrical signals and send them to a machine called electroencephalograph It records the signals as wavy lines on to a computer screen or paper in order of microvolt

Electroencephalograph is a device used in the diagnosis and detection of brain abnormalities

Electroencephalogram is the visual output that an Electroencephalograph produces

Biological aspects

Human brain basic structure and functions

The brain is composed of the cerebrum, cerebellum, and brainstem

The **cerebrum** is the largest part of the brain and is composed of right and left hemispheres. It performs higher functions like interpreting touch, vision and hearing, as well as speech, reasoning, emotions, learning, and fine control of movement.

The **cerebellum** is located under the cerebrum. Its function is to coordinate muscle movements, maintain posture, and balance.

The **brainstem** includes the midbrain, pons, and medulla. It acts as a relay centre connecting the cerebrum and cerebellum to the spinal cord. It performs many automatic functions such as breathing, heart rate, body temperature, wake and sleep cycles, digestion, sneezing, coughing, vomiting, and swallowing. Ten of the twelve cranial nerves originate in the brainstem.

Right brain – left brain

The right and left hemispheres of the brain are joined by a bundle of fibers called the corpus callosum that delivers messages from one side to the other. Each hemisphere controls the opposite side of the body. If a brain tumor is located on the right side of the brain, your left arm or leg may be weak or paralyzed.

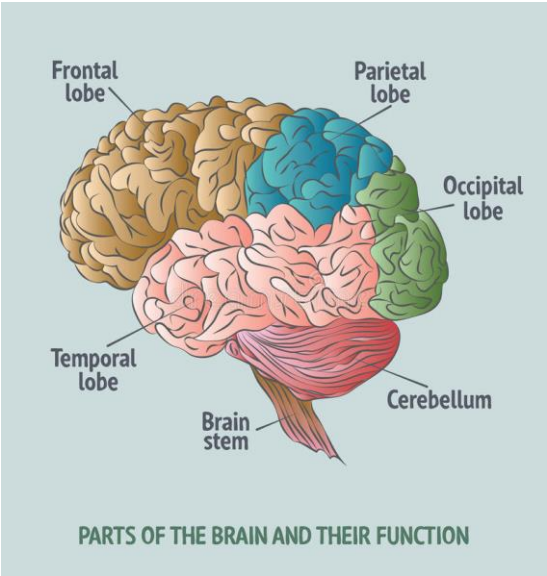
Not all functions of the hemispheres are shared. In general, the left hemisphere controls speech, comprehension, arithmetic, and writing. The right hemisphere controls creativity, spatial ability, artistic, and musical skills. The left hemisphere is dominant in hand use and language in about 92% of people.

Lobes of the brain

The cerebral hemispheres have distinct fissures, which divide the brain into lobes. Each hemisphere has 4 lobes: frontal, temporal, parietal, and occipital. Each lobe may be divided, once again, into areas that serve very specific functions. It's important to understand that each lobe of the brain does not function alone. There are very complex relationships between the lobes of the brain and between the right and left hemispheres.

Frontal lobe

- Personality, behavior, emotions
- Judgment, planning, problem solving
- Speech: speaking and writing (Broca's area)
- Body movement (motor strip)
- Intelligence, concentration, self awareness



Parietal lobe

- Interprets language, words
- Sense of touch, pain, temperature (sensory strip)
- Interprets signals from vision, hearing, motor, sensory and memory

- Spatial and visual perception

Occipital lobe

- Interprets vision (color, light, movement)
- Temporal lobe
- Understanding language (Wernicke's area)
- Memory
- Hearing
- Sequencing and organization

Electroencephalography (EEG)

The brain's electrical charge is maintained by billions of neurons. Neurons are electrically charged (or "polarized") by membrane transport proteins that pump ions across their membranes. Neurons are constantly exchanging ions with the extracellular milieu, for example to maintain resting potential and to propagate action potentials. Ions of similar charge repel each other, and when many ions are pushed out of many neurons at the same time, they can push their neighbors, who push their neighbors, and so on, in a wave. This process is known as volume conduction.

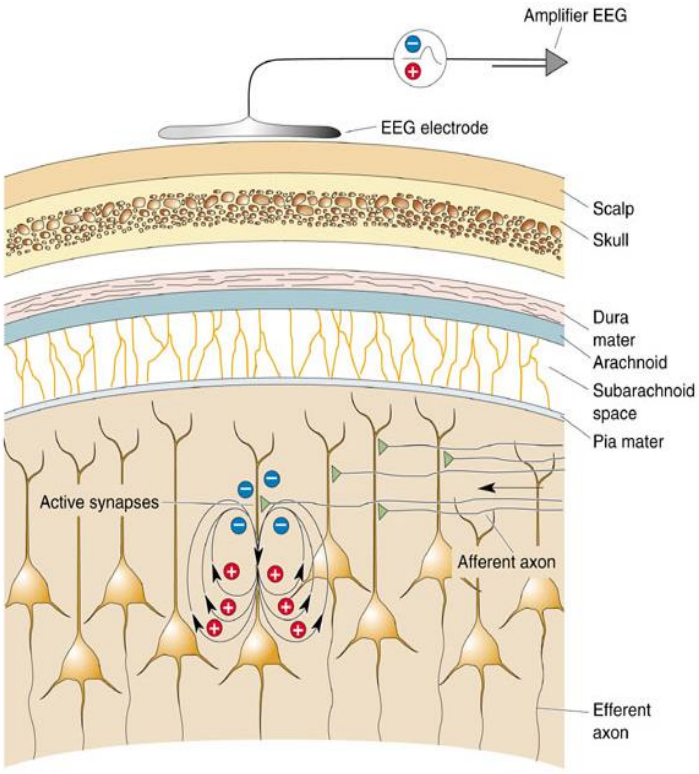
When the wave of ions reaches the electrodes on the scalp, they can push or pull electrons on the metal in the electrodes. Since metal conducts the push and pull of electrons easily, the difference in push or pull voltages between any two electrodes can be measured by a voltmeter. Recording these voltages over time gives us the EEG.

The electric potential generated by an individual neuron is far too small to be picked up by EEG or MEG. EEG activity therefore always reflects the summation of the synchronous activity of thousands or millions of neurons that have similar spatial orientation. If the cells do not have similar spatial orientation, their ions do not line up and create waves to be detected.

Encephalograph

Encephalographic measurements employ recording system consisting of

- Electrodes with conductive media
- Amplifiers with filters
- A/D converter
- Recording device.



Recording electrodes

The EEG recording electrodes and their proper function are critical for acquiring appropriately high-quality data for interpretation. In most clinical applications, 19 recording electrodes (plus ground and system reference) are used. A smaller number of electrodes are typically used when recording EEG from neonates. Additional electrodes can be added to the standard set-up when a clinical or research application demands increased spatial resolution for a particular area of the brain. High-density arrays (typically via cap or net) can contain up to 256 electrodes more-or-less evenly spaced around the scalp.

Many types of electrodes exist, often with different characteristics. Basically, there are following types of electrodes:

Disposable (gel-less, and pre-gelled types)

Reusable disc electrodes (gold, silver, stainless)

Headbands and electrode caps

Saline-based electrodes

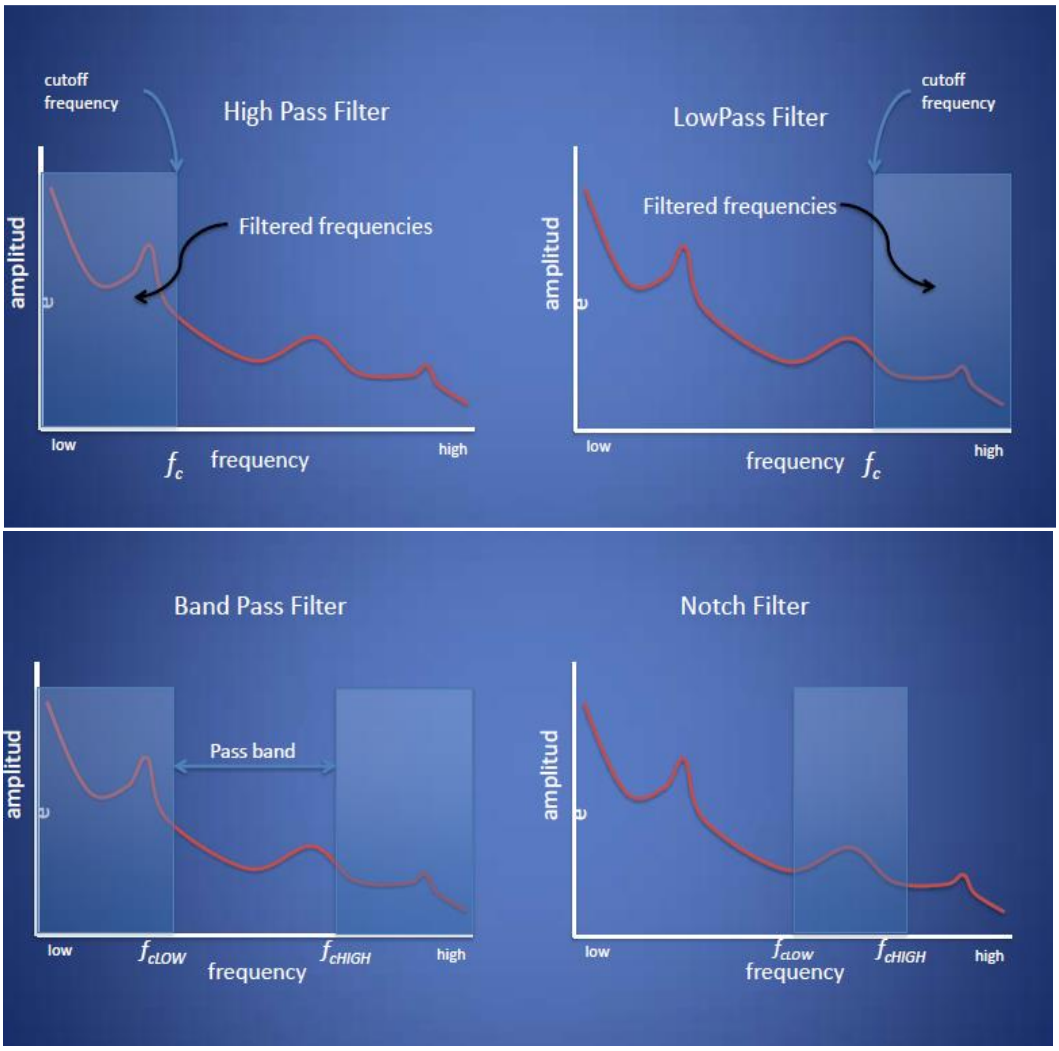
Needle electrodes

Amplifiers

The signals need to be amplified to make them compatible with devices such as displays, recorders, or A/D converters. They have to provide amplification selective to the physiological signal, reject superimposed noise and interference signals, and guarantee protection from damages through voltage and current surges for both patients and electronic equipment.

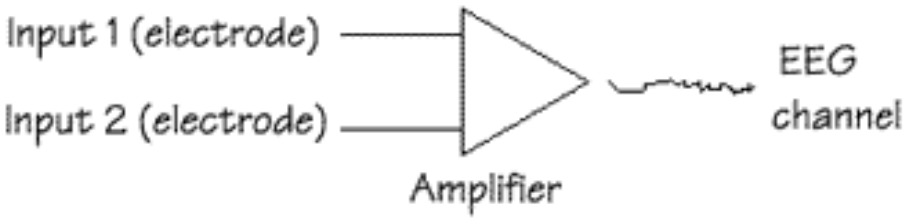
Filters

The recorded signals are built up from different frequency components. With filters an appropriate frequency band can be chosen to filter out the unnecessary frequency components. There are low-pass, high-pass, band-pass and band-stop filters.

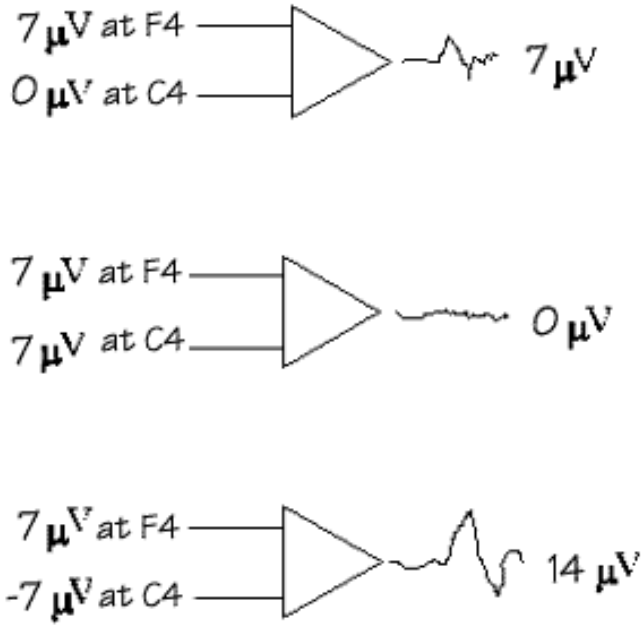


EEG montage

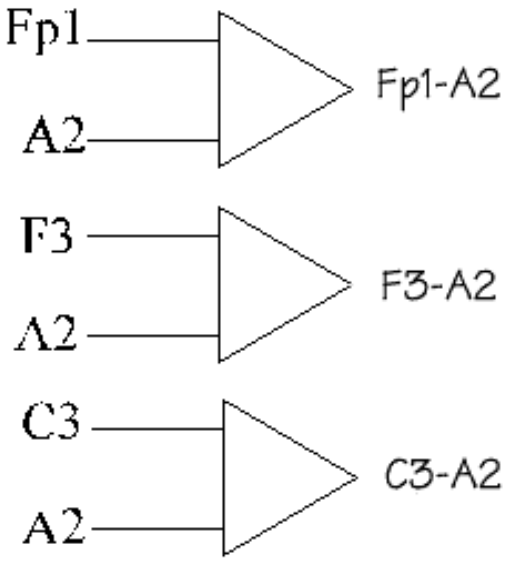
EEG machines use a differential amplifier to produce each channel or trace of activity. Each amplifier has two inputs. An electrode is connected to each of the inputs.



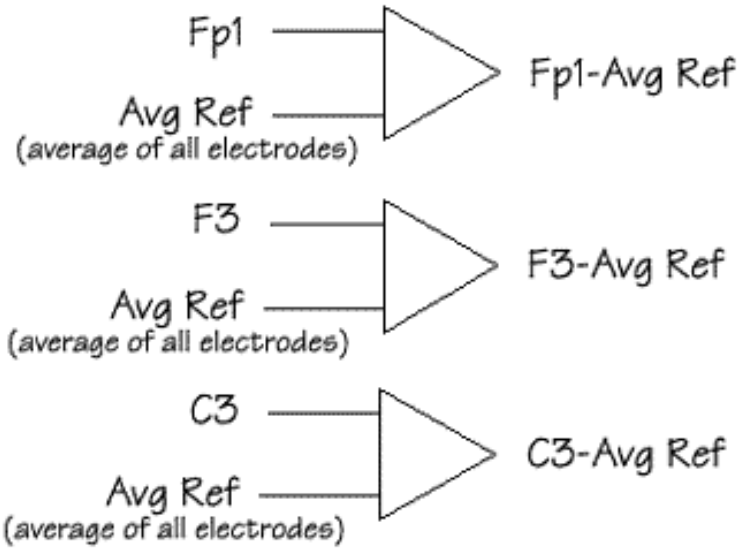
Differential amplifiers measure the voltage difference between the two signals at each of its inputs. The resulting signal is amplified and then displayed as a channel of EEG activity.



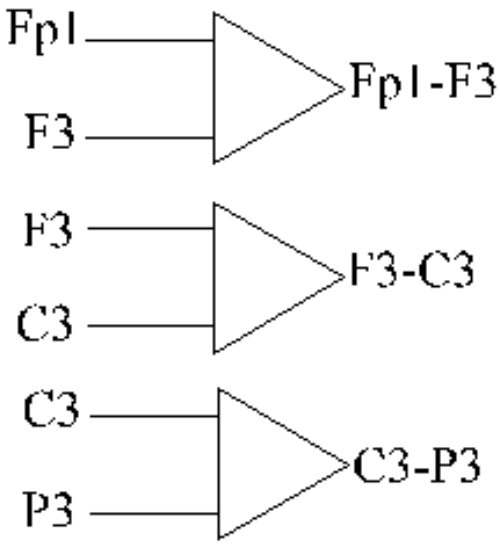
Common reference derivation: Each amplifier records the difference between a scalp electrode and a reference electrode. The same reference electrode is used for all channels. Electrodes frequently used as the reference electrode are A1, A2, the ear electrodes, or A1 and A2 linked together.



Average reference derivation: Activity from all the electrodes are measured, summed together and averaged before being passed through a high value resistor. The resulting signal is then used as a reference electrode and connected to input 2 of each amplifier and is essentially inactive. All EEG systems will allow the user to choose which electrodes are to be included in this calculation.



Bipolar derivation: These sequentially link electrodes together usually in straight lines from the front to the back of the head or transversely across the head. For example the first amplifier may have electrodes FP1 and F3 connected to it and the second amplifier F3 and C3 connected to it.

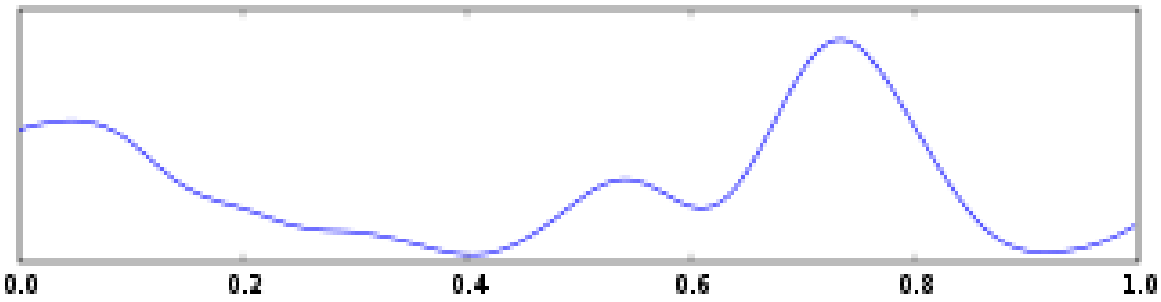


Electroencephalogram

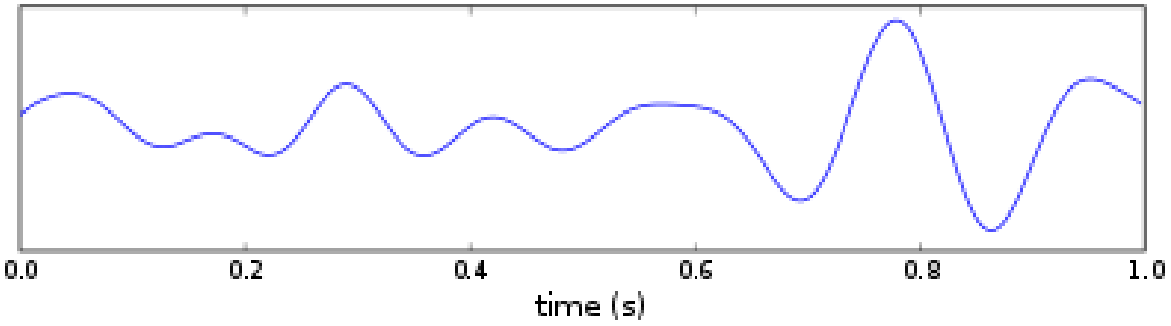
The electroencephalogram (EEG) is the depiction of the electrical activity occurring at the surface of the brain. This activity appears on the screen of the EEG machine as waveforms of varying frequency and amplitude measured in voltage (specifically microvoltages).

EEG waveforms are generally classified according to their frequency, amplitude, and shape, as well as the sites on the scalp at which they are recorded. The most familiar classification uses EEG waveform frequency (eg, alpha, beta, theta, and delta).

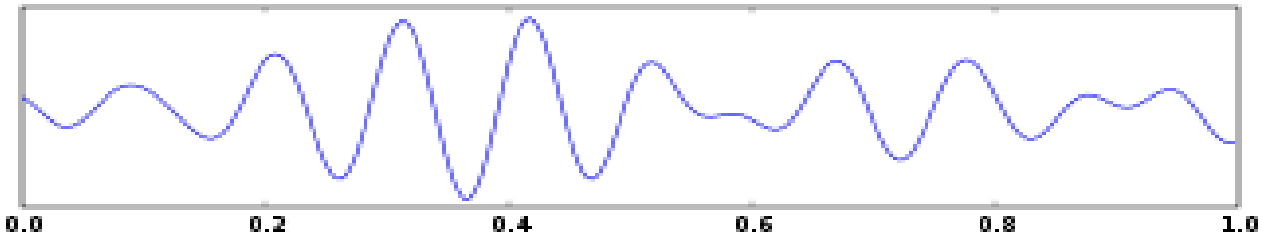
Delta: has a frequency of 4 Hz or below. It tends to be the highest in amplitude and the slowest waves. It is normal as the dominant rhythm in infants up to one year and in stages 3 and 4 of sleep. It may occur focally with subcortical lesions and in general distribution with diffuse lesions, metabolic encephalopathy hydrocephalus or deep midline lesions. It is usually most prominent frontally in adults



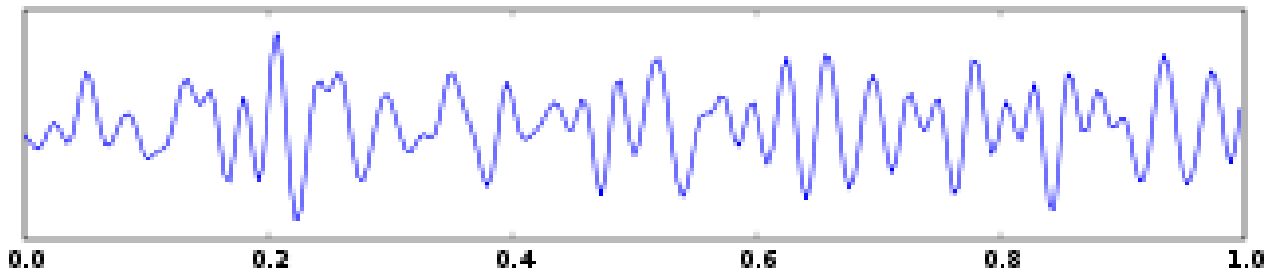
Theta: has a frequency of 4 to 7 Hz and is classified as "slow" activity. It is perfectly normal in children up to 13 years and in sleep but abnormal in awake adults.



Alpha: has a frequency between 7 and 14 Hz. Is usually best seen in the posterior regions of the head on each side, being higher in amplitude on the dominant side. It appears when closing the eyes and relaxing and disappears when opening the eyes or alerting by any mechanism (thinking, calculating). It is the major rhythm seen in normal relaxed adults. It is present during most of life especially after the thirteenth year.



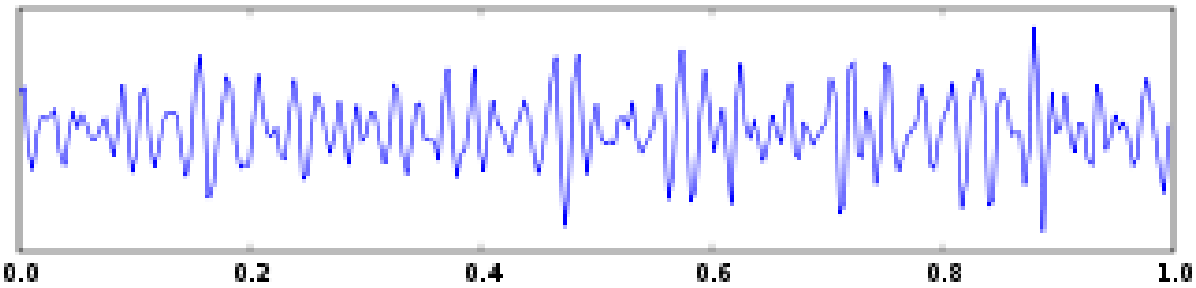
Beta: beta activity is "fast" activity. It has a frequency range approximately 14–25 Hz of. It is usually seen on both sides in symmetrical distribution and is most evident frontally. It is generally regarded as a normal rhythm. It is the dominant rhythm in patients who are alert or anxious or have their eyes open.



Gamma is the frequency range approximately 25–100 Hz. Gamma brain waves are the fastest brainwave frequency with the smallest amplitude. They are associated with the "feeling of blessings" reported by experienced meditators such as monks and nuns, and with peak concentration and extremely high levels of cognitive functioning.

Neuroscientists believe that gamma waves are able to link information from all parts of the brain and not only that, but the entire brain is influenced by the gamma wave.

Everyone has gamma brainwave activity, but the amount of gamma waves produced varies. Low amounts of gamma brainwave activity have been linked to learning difficulties, poor memory and impaired mental processing.



Medical uses of EEG

An EEG is mainly used when there is a need to diagnose and manage epilepsy

It can also be used to investigate other conditions such as encephalitis, dementia, head injuries, brain tumors, hemorrhage

An EEG can identify areas of the brain that are not working properly

EEGs are also used to determine the level of brain function in people who are in a coma.

Advantages of EEG

Hardware costs are significantly lower than those of most other techniques

EEG has very high temporal resolution, on the order of milliseconds rather than seconds

Extremely non-invasive

EEG is silent, which allows for better study of the responses to auditory stimuli

EEG does not involve exposure to high-intensity (>1 Tesla) magnetic fields.

Disadvantages of EEG

Low spatial resolution on the scalp

EEG determines neural activity that occurs below the upper layers of the brain poorly

Often takes a long time to connect a subject to EEG

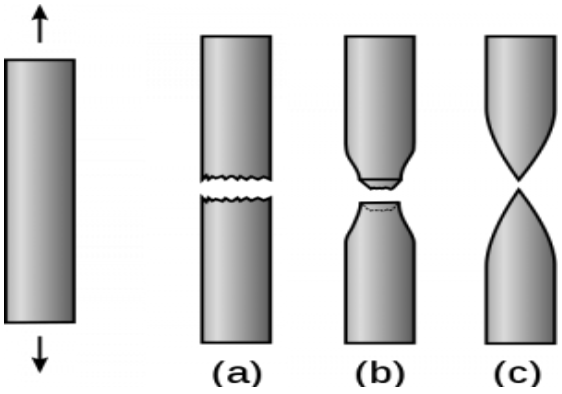
Signal-to-noise ratio is poor

Elasticity of the human bone and tendon

Bones, on the whole, do not fracture due to tension or compression. Rather they generally fracture due to sideways impact or bending, resulting in the bone shearing or snapping. The behavior of bones under tension and compression is important because it determines the load the bones can carry. Bones are classified as weight-bearing structures such as columns in buildings and trees. Weight-bearing structures have special features; columns in building have steel-reinforcing rods while trees and bones are fibrous. The bones in different parts of the body serve different structural functions and are prone to different stresses. Thus the bone in the top of the femur is arranged in thin sheets separated by marrow while in other places the bones can be cylindrical and filled with marrow or just solid. Overweight people have a tendency toward bone damage due to sustained compressions in bone joints and tendons.

Brittle Bones

Brittle materials have a small plastic region and they begin to fail toward fracture or rupture almost immediately after being stressed beyond their elastic limit. Bone, cast iron, ceramic, and concrete are examples of brittle materials. Materials that have relatively large plastic regions under tensile stress are known as ductile. Examples of ductile materials include aluminum and copper. The following figure shows how brittle and ductile materials change shape under stress. Even the cartilage that makes up tendons and ligaments is relatively brittle because it behaves less like example (c) and more like examples (a) and (b). Luckily, those tissues have adapted to allow the deformation required for typical movement without the brittle nature of the materiel coming into play. We will learn about that adaptation in the next chapter.



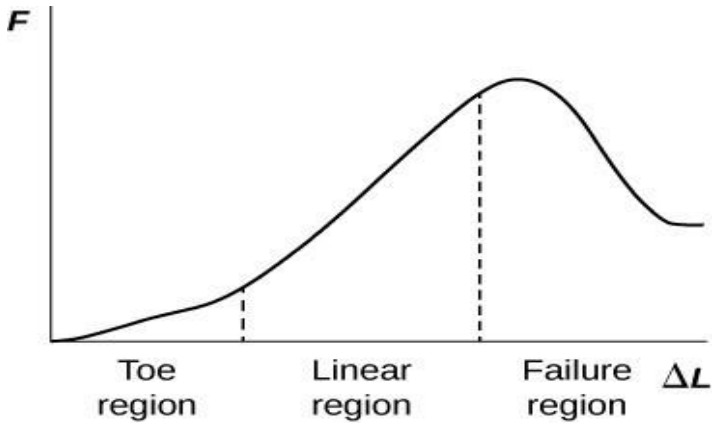
Profile (a) is an example of the material that fractures with no plastic deformation, i.e., it is a brittle material. Profile (b) is an example of a material that fractures after very little plastic deformation. These two profiles would be classified as having low ductility. Profile (c) in contrast is a material that plastically deforms before fracture. This material has high ductility. Image Credit:

Materials that are very malleable can undergo significant plastic deformation under compressive stress, as opposed to tensile stress. Very malleable materials can be pounded into thin sheets. Gold is the most malleable metal.

Tendon

Another biological example of Hooke's law occurs in tendons. Functionally, the tendon (the tissue connecting muscle to bone) must stretch easily at first when a force is applied but offer a much greater restoring force for a greater strain. Figure shows a stress-strain relationship for a human tendon. Some tendons have a high collagen content so there is relatively little strain, or length change; others, like support tendons (as in the leg) can change length up to 10%. Note that this stress-strain curve is nonlinear, since the slope of the line changes in different regions. In the first part of the stretch called the toe region, the fibers in the tendon begin to align in the direction of the stress—this is called *uncrimping*. In the linear region, the fibrils will be stretched, and in the failure region individual fibers begin to break. A simple model of this relationship can be illustrated by springs in parallel: different springs are activated

at different lengths of stretch. Examples of this are given in the problems at end of this chapter. Ligaments (tissue connecting bone to bone) behave in a similar way.



Typical stress-strain curve for mammalian tendon. Three regions are shown: (1) toe region (2) linear region, and (3) failure region.

Unlike bones and tendons, which need to be strong as well as elastic, the arteries and lungs need to be very stretchable. The elastic properties of the arteries are essential for blood flow. The pressure in the arteries increases and arterial walls stretch when the blood is pumped out of the heart. When the aortic valve shuts, the pressure in the arteries drops and the arterial walls relax to maintain the blood flow. When you feel your pulse, you are feeling exactly this—the elastic behavior of the arteries as the blood gushes through with each pump of the heart. If the arteries were rigid, you would not feel a pulse. The heart is also an organ with special elastic properties. The lungs expand with muscular effort when we breathe in but relax freely and elastically when we breathe out. Our skins are particularly elastic, especially for the young. A young person can go from 100 kg to 60 kg with no visible sag in their skins. The elasticity of all organs reduces with age. Gradual physiological aging through reduction in elasticity starts in the early 20s.

Example : Calculating Deformation: How Much Does Your Leg Shorten When You Stand on It?

Calculate the change in length of the upper leg bone (the femur) when a 70.0 kg man supports 62.0 kg of his mass on it, assuming the bone to be equivalent to a uniform rod that is 40.0 cm long and 2.00 cm in radius.

Strategy

The force is equal to the weight supported, or

$F=mg=(62.0kg)(9.80m/s^2)=607.6N$,

and the cross-sectional area is $\pi r^2=1.257\times10^{-3}m^2$. To find the change in length, we can use the equation:

$$\Delta L = \frac{1}{Y}\frac{F}{A}L_0$$

Solution

All quantities except ΔLΔL are known. Note that the compression value for Young's modulus for bone must be used here. Thus,

$$\Delta L = \left(\frac{1}{9x10^9 N/m^2}\right)\left(\frac{607.6\ N}{1.257x10^{-3}}\right)(0.4m)$$

$= 2x10^{-5}$ m

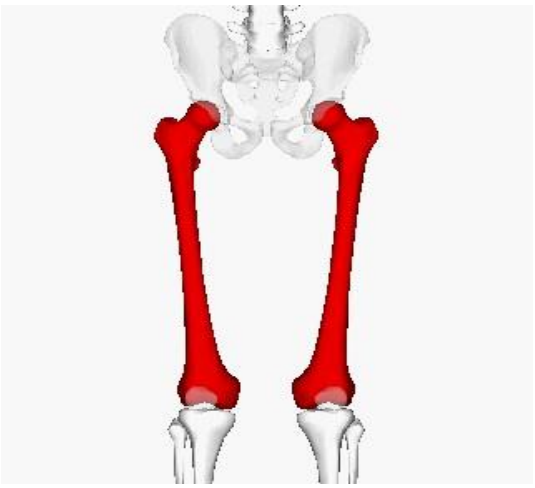
Discussion

This small change in length seems reasonable, consistent with our experience that bones are rigid. In fact, even the rather large forces encountered during strenuous physical activity do not compress or bend bones by large amounts. Although bone is rigid compared with fat or muscle, several of the substances listed in Table have larger values of Young's modulus YY. In other words, they are more rigid.

Strength of Human Bones

The Femur

"In human anatomy, the femur (thigh bone) is the longest and largest bone. Along with the temporal bone of the skull, it is one of the two strongest bones in the body. The average adult male femur is 48 cm (18.9 in) in length and 2.34 cm (0.92 in) in diameter and can support up to 30 times the weight of an adult."

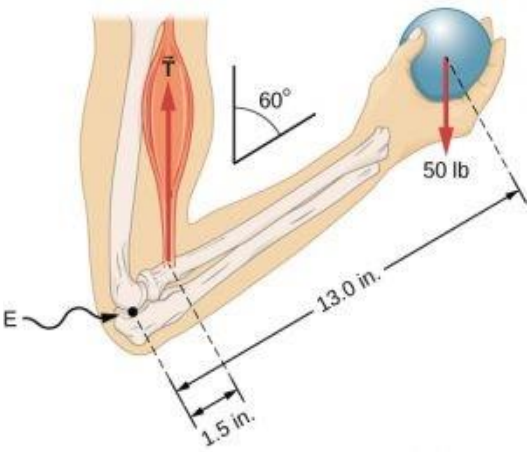


Compression

When you place an object on top of a structure, the object's weight tends to compress the structure. Any push that tends to compress a structure is called a compressive force. The average weight among adult males in the United States is 196 lbs (872 N). According to the statement that the femur can support 30x body weight, the adult male femur can support roughly 6,000 lbs of compressive force! Such high forces are rarely generated by the body under its own power; thus motor vehicle collisions are the number one cause of femur fractures.

Tension

When you hang an object from a structure the object's weight will tend to stretch the structure. The structure responds by providing a tension force to hold up the object. Tension forces are restoring forces produced in response to materials being stretched. Non-rigid objects like ropes, cables, chains, muscles, tendons, can effectively provide tension forces *only*, while rigid object can

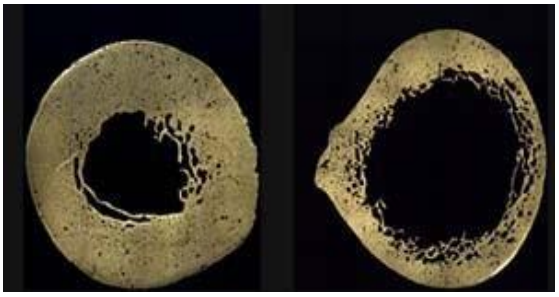


supply compression and tension forces. For example, the biceps muscle is providing a tension (*T*) force on the thumb-side forearm bone (radius bone).

The elbow joint flexed to form a 60° angle between the upper arm and forearm while the hand holds a 50 lb ball.

Stress

The maximum compression or tension forces that a bone can support depends on the size of the bone. More specifically, the more area available for the force to be spread out over, the more force the bone can support. That means the maximum forces bones, (and other objects) can handle are proportional to the cross-sectional area of the bone that is perpendicular (90°) to the direction of the force. For example, the force that the femur can support vertically along its length depends on the area of its horizontal cross-section which is roughly circular and somewhat hollow (bone marrow fills the center space).



These cross sections show the midshaft of the femur of an 84-year-old female with advanced osteoporosis (right), compared to a healthy femur of a 17-year-old female (left). Image Credit: Smithsonian National Museum of Natural History.

Larger bones can support more force, so in order to analyze the behavior of the bone material itself we need to divide the force applied to the bone by the minimum cross-sectional area (A). This quantity is known as the stress on the material. Stress has units of force per area, so the SI units are (N/m^2) which are also known as Pascals. Units of pounds per square inch (PSI, lbs/in^2) are common in the U.S.

$$stress = \frac{F}{A}$$

Quiz

Estimate the compressive stress within a 1.0 cm x 2.0 cm Lego block when you step on it with full body weight in units of Pascals.

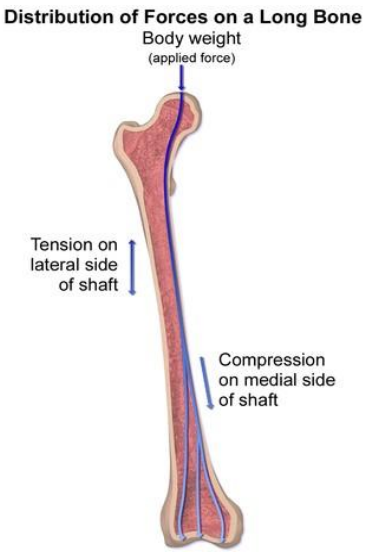
Ultimate Strength of the Femur

The maximum stress that bone, or any other material, can experience before the material begins fracture or rupture is called the ultimate strength. Notice that material strength is defined in terms of stress, not force, so that we are analyzing the material itself, without including the effect of *how much* material is present. For some materials the ultimate strength is different when the stress is acting to crush the material (compression) versus when the forces are acting to stretch the material under tension, so we often refer to ultimate tensile strength or ultimate compressive strength. For example, the ultimate compressive strength for human femur bone is measured to be 205 MPa (205 Million Pascals) under compression along its length. The ultimate tensile strength of femur bone under tension along its length is 135 MPa. Along with bone, concrete and chalk are other examples of materials with different compressive and tensile ultimate strengths.

Transverse Ultimate Strength

So far we have discussed ultimate strengths along the long axis of the femur, known as the longitudinal direction. Some materials, such as bone and wood, have different ultimate strengths along different axes. The ultimate compressive strength for bone along the short axis (transverse direction) is 131 MPa, or about 36% less than the 205 MPa longitudinal value. Materials that have different properties along different axes are known as anisotropic. Materials that behave the same in all directions are called isotropic.

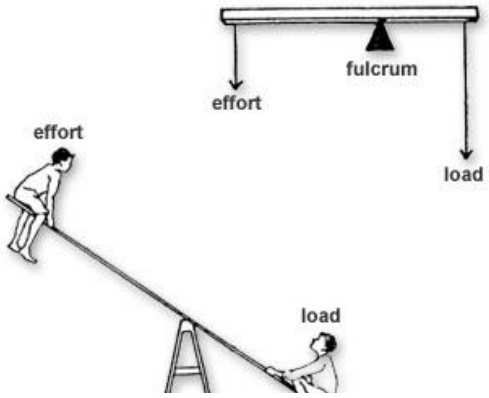
An interesting fact to finish up this section: when a person stands the femur actually experiences compressive and tensile stresses on different sides of the bone. This occurs because the structure of the hip socket applies the load of the body weight off to the side rather than directly along the long axis of the bone.



Both tension and compressive stresses are applied to the Femur while standing.

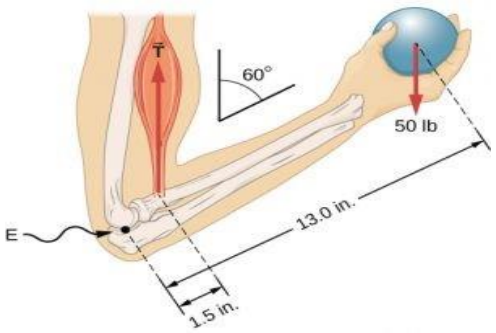
Levers

A lever is a rigid object used to make it easier to move a large load a short distance or a small load a large distance. There are three classes of levers, and all three classes are present in the body.



For example, the forearm is a 3rd class lever because the biceps pull on the forearm between the joint (fulcrum) and the ball (load).

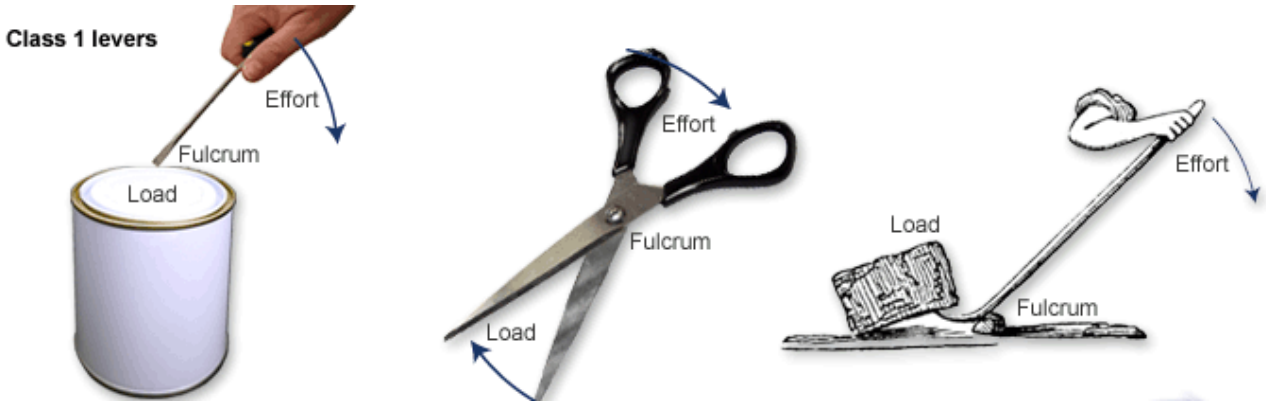
The elbow joint flexed to form a 60° angle between the upper arm and forearm while the hand holds a 50 lb ball.



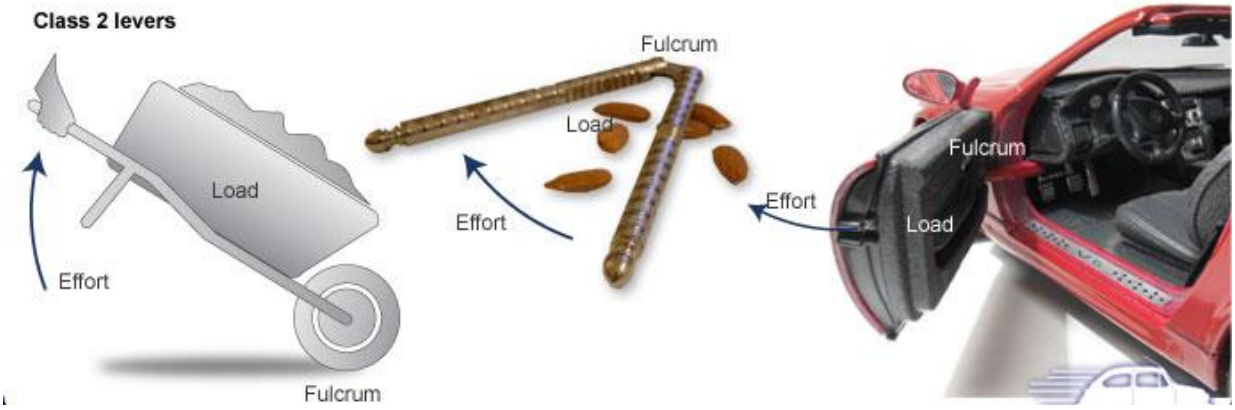
Lever Classes

Using the standard terminology of levers, the forearm is the lever, the biceps tension is the effort, the elbow joint is the fulcrum, and the ball weight is the resistance. When the resistance is caused by the weight of an object, we call it the load. The lever classes are identified by the relative location of the resistance, fulcrum and effort.

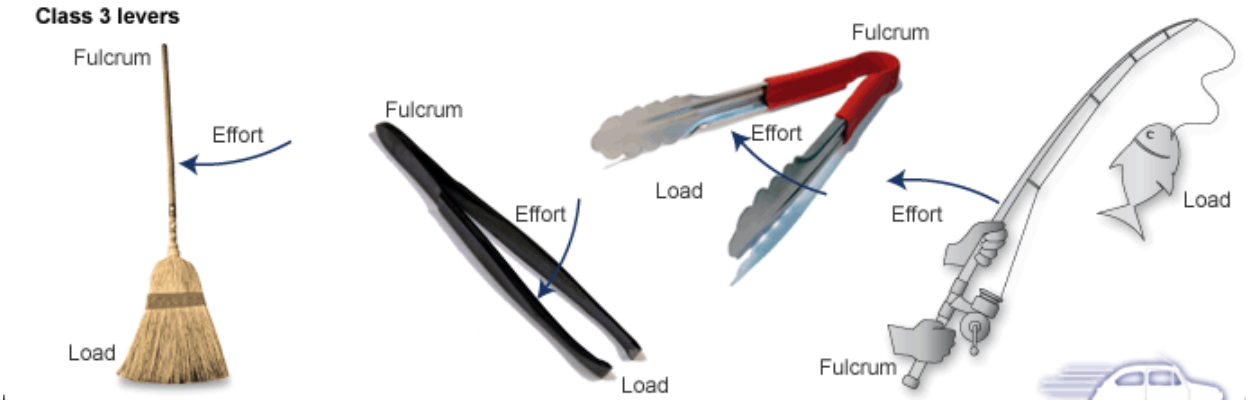
- **First class levers have the fulcrum in the middle, between the load and resistance.**



- **Second class levers have resistance in the middle.**



- **Third class levers have the effort in the middle.**



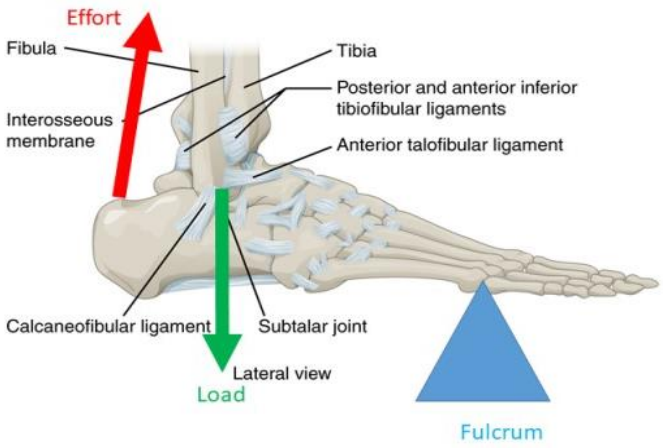
For all levers the effort and resistance (load) are actually just forces that are creating torques because they are trying to rotate the lever. In order to move or hold a load the torque created by the effort must be large enough to balance the torque caused by the load. Remembering that torque increases as the force is applied farther from the pivot,

the effort needed to balance the resistance must depend on the distances of the effort and resistance from the pivot. These distances are known as the effort arm and resistance arm *(*load arm*)*.

Quiz

Identify the class of lever created by the foot and the calf muscle when raising the heel off the ground.

What class lever is it? The mnemonic = FRE



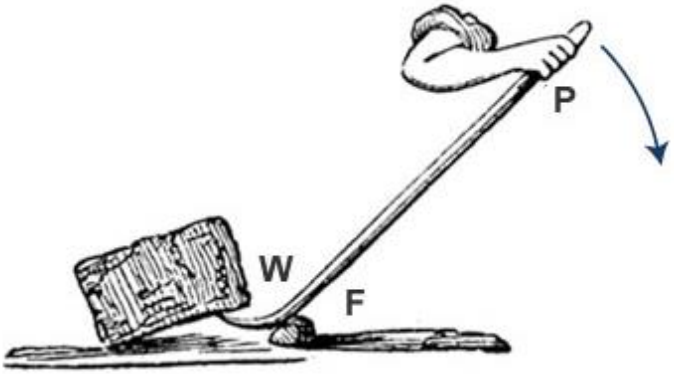
One way to remember the classes of lever is to think "FRE" or "free," as in: "I want to be free of confusion about levers."

- **The F stands for fulcrum, in the middle of a class 1 lever (e.g., seesaw).**
- **The R stands for resistance (which is the same thing as the load), and it is in the middle of a class 2 lever (e.g., wheelbarrow).**
- **The E stands for effort, which is in the middle of a class 3 lever (e.g., broom).**

Characteristics of class 1 levers

First-class levers always change the direction of the force. In other words, if the effort is "down," the load moves "up."

First-class levers can be used to affect the force on the load, the distance through which the load moves, and the speed with which it moves. If the fulcrum is close to the load and far from the effort, the force is increased but the effort must move through a greater distance or with a greater speed to move the load.



Fulcrum close to the load in a class 1 lever

If, on the other hand, the fulcrum is close to the effort, the force is not as much increased but the load moves through a greater distance or with a greater speed.

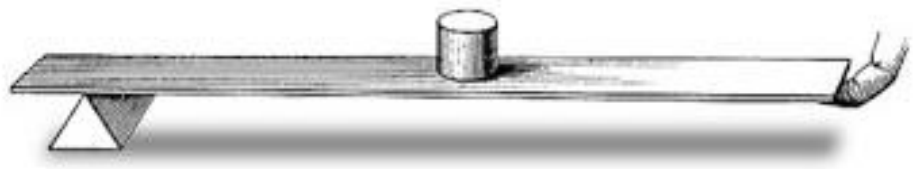
The mechanical advantage of a first class lever can be greater than 1 or less than 1, depending on the location of the fulcrum relative to the load and effort.

Fulcrum closer to the effort in a class 1 lever

Characteristics of class 2 levers

A second-class lever does not change the direction of the force (if the effort force points "up," the load moves "up").

The second-class lever always confers a mechanical advantage because the "effort arm" or distance from the fulcrum to the effort is greater than the "load arm" or distance from the fulcrum to the load.



Characteristics of class 3 levers

Like a second-class lever, a third-class lever does not change the direction of the force.

The interesting thing about third-class levers is that they do not confer a mechanical advantage. The mechanical advantage of a third-class lever is less than 1!

What, then, is the use of third-class levers? They always produce a gain in the speed (or distance covered per unit time) of the load. Sometimes the gain in speed of the load is useful in itself.

Levers in the body

The bones in the human body act as levers, with the joints fulfilling the role of pivot points. The muscles provide the effort, and the weights of segments of the body — or external weights — provide the load.

The human body provides examples of first, second, and third-class levers. First and third class levers are the most common in the body.

As we saw in the last section, a characteristic of third-class levers is that they confer no mechanical advantage. And the first-class levers in the body often operate with a mechanical advantage less than 1. The human body is built for speed, rather than mechanical advantage!

First-class levers in the human body

An example of a first-class lever is provided by the head, top of the spine, and neck muscles. The fulcrum of this system is the joint between the occipital bone at the base of the skull and the atlas, the first vertebra of the neck. The weight of the head is like the load, tending to rotate the head forward and down (as one might move if looking through a microscope or writing at a desk). The neck extensor muscles exert the effort to hold the head up.

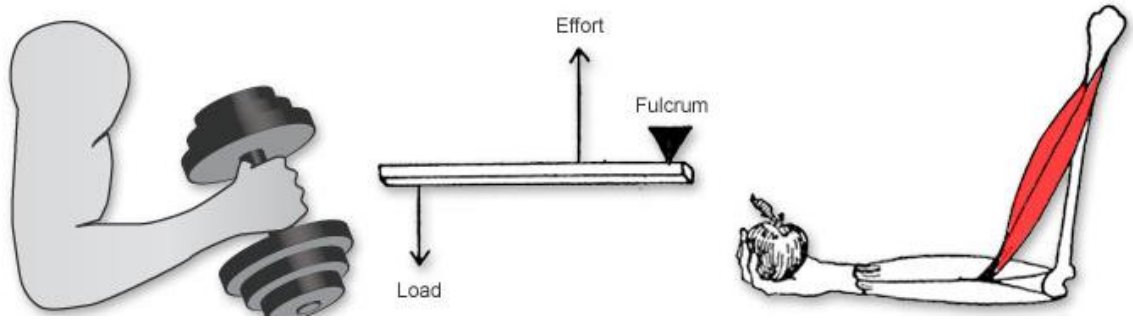
Second-class levers in the human body

When you do a press-up from the floor, your head, neck, trunk, and legs form a lever that has the balls of the feet as fulcrum. The action of the arms raises the load. This is an example of a second-class lever, with the effort at one end, the load in the middle, and the fulcrum at the other end.

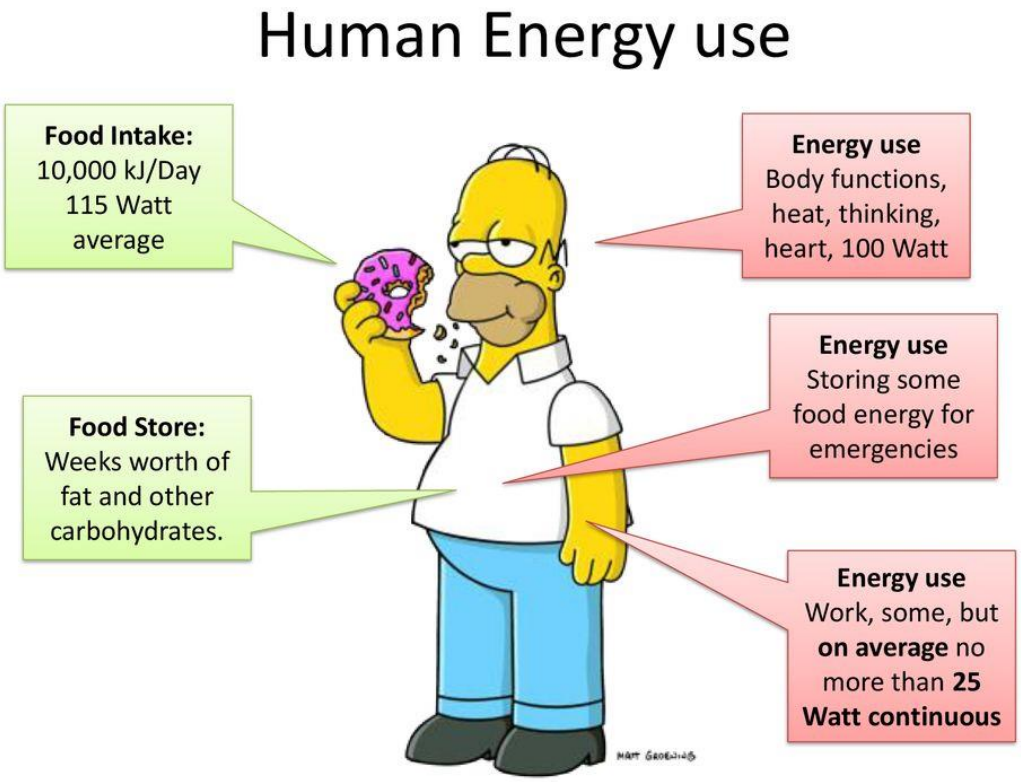
Third-class levers in the human body

A biceps curl is an example of a third-class lever. The load is the weight held in the hand, the fulcrum is the elbow joint and the effort is provided by the bicep muscles of the arm.

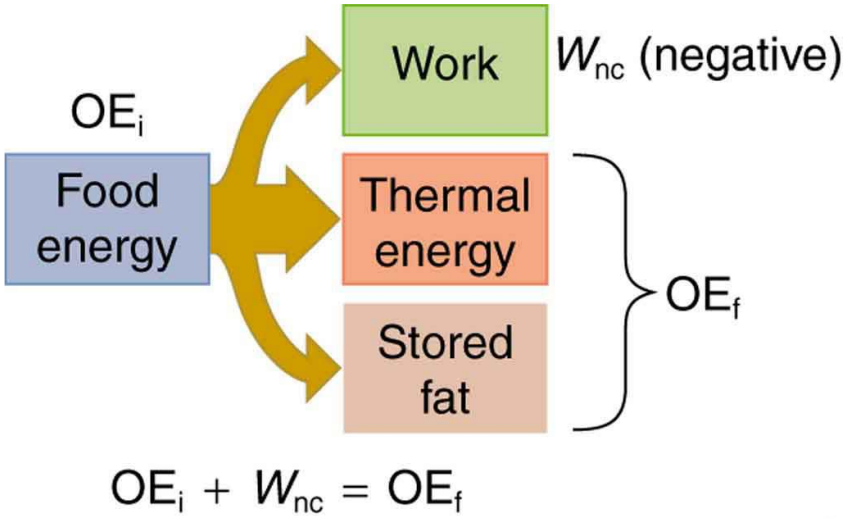
The contraction of the muscles in the upper arm pulls the lower arm up. The muscles move a short distance compared to the end of the lever (the lower arm). The speed of movement in the lower arm is helpful for throwing a ball or swinging a tennis racket.



Work, Energy, and Power in Humans



Our own bodies, like all living organisms, are energy conversion machines. Conservation of energy implies that the chemical energy stored in food is converted into work, thermal energy, and/or stored as chemical energy in fatty tissue. The fraction going into each form depends both on how much we eat and on our level of physical activity. If we eat more than is needed to do work and stay warm, the remainder goes into body fat.



Power Consumed at Rest

The *rate* at which the body uses food energy to sustain life and to do different activities is called the metabolic rate. The total energy conversion rate of a person *at rest* is called the basal metabolic rate (BMR) and is divided among various systems in the body, as shown in the following Table. The largest fraction goes to the liver and spleen, with the brain coming next. Of course, during vigorous exercise, the energy consumption of the skeletal muscles and heart increase markedly. About 75% of the calories burned in a day go into these basic functions. The BMR is a function of age, gender, total body weight, and amount of muscle mass (which burns more calories than body fat). Athletes have a greater BMR due to this last factor.

Organ	Power consumed at rest (W)	Oxygen consumption (mL/min)	Percent of BMR
Liver & spleen	**23**	**67**	**27**
Brain	**16**	**47**	**19**
Skeletal muscle	**15**	**45**	**18**

Kidney	**9**	**26**	**10**
Heart	**6**	**17**	**7**
Other	**16**	**48**	**19**
Totals	**85W**	**250mL/min**	**100%**

Energy consumption is directly proportional to oxygen consumption because the digestive process is basically one of oxidizing food. We can measure the energy people use during various activities by measuring their oxygen use. Approximately 20 kJ of energy are produced for each liter of oxygen consumed, independent of the type of food.

How is energy stored in the body?

The ultimate source of all energy on earth is the sun. Solar energy is harnessed by plants, which take carbon, hydrogen, oxygen, and nitrogen from their environment and manufacture either carbohydrate, fat, or protein. These foods possess stored energy. When we consume these foods, our digestive processes break them down into simple compounds that are absorbed into the body and transported to various cells. One of the basic purposes of body cells is to transform the chemical energy of these simple compounds into forms that may be available for immediate use or other forms that may be available for future use.

Energy in the body is available for immediate use in the form of adenosine triphosphate (ATP). It is a complex molecule constructed with high-energy bonds, which, when split by enzyme action, can release energy rapidly for a number of body processes, including muscle contraction. ATP is classified as a high-energy compound and is stored in the tissues in small amounts. It is important to note that ATP is the immediate source of energy for all body functions, and the other energy stores are used to replenish ATP at varying rates. Another related high-energy phosphate compound, phosphocreatine (PCr), is also found in the tissues in small amounts. Although it cannot

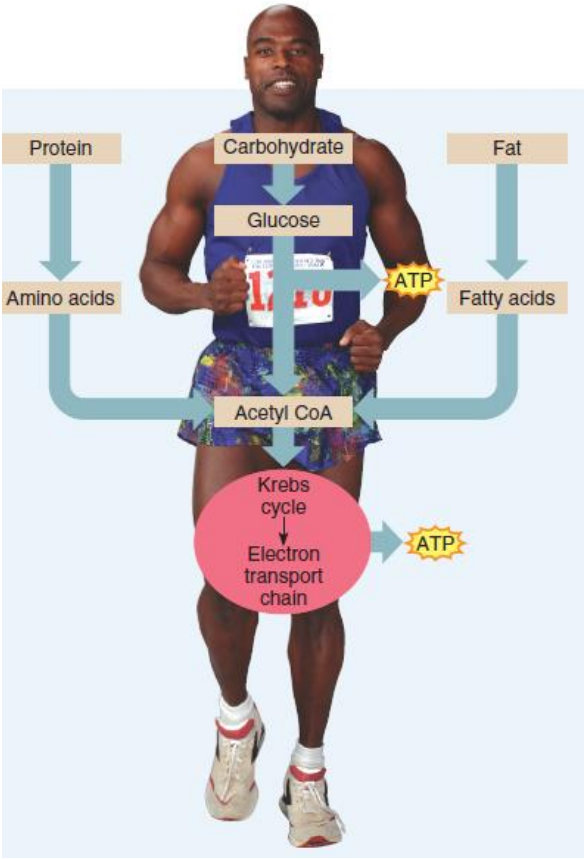
be used as an immediate source of energy, it can rapidly replenish ATP. ATP may be formed from either carbohydrate, fat, or protein after those nutrients have undergone some complex biochemical changes in the body.

Because ATP and PCr are found in very small amounts in the body and can be used up in a matter of seconds, it is important to have adequate energy stores as a backup system. Your body stores of carbohydrate, fat, and protein can provide you with ample amounts of ATP, enough to last for many weeks even on a starvation diet. It is important to note that parts of each energy nutrient may be converted to the other two nutrients in the body under certain circumstances. For example, protein may be converted into carbohydrate during prolonged exercise, whereas excess dietary carbohydrate may be converted to fat in the body during rest.

Human energy systems

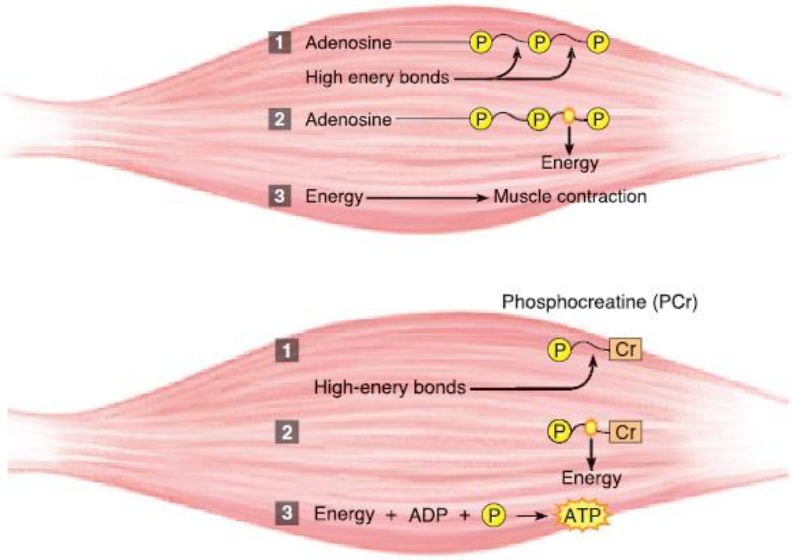
Sometimes humans needed to produce energy at a rapid rate, such as when sprinting to safety to avoid dangerous animals. Thus, a fast rate of energy production was an important human energy feature that helped ensure survival. At other times, our ancient ancestors may have been deprived of adequate food for long periods, and thus needed a storage capacity for chemical energy that would sustain life throughout these times of deprivation. Hence, the ability to store large amounts of energy was also important for survival. These two factors—rate of energy production and energy capacity—appear to be determining factors in the development of human energy systems.

The human energy expenditure system can be classified to three energy, or power, systems: the ATP-PCr system, the lactic acid system, and the oxygen system.



- The ATP-PCr system is also known as the phosphagen system because both adenosine triphosphate (ATP) and phosphocreatine (PCr) contain phosphates. ATP is the immediate source of energy for almost all body processes, including muscle contraction. This high-energy compound, stored in the muscles, rapidly releases energy when an electrical impulse arrives in the muscle. No matter what you do, scratch your nose or lift 100 pounds, ATP breakdown makes the movement possible. ATP must be present for the muscles to contract. The body has a limited supply of ATP and must replace it rapidly if muscular work is to continue.

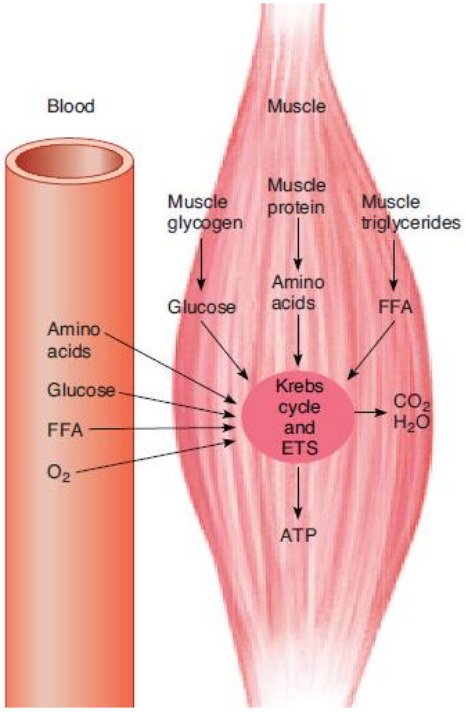
  PCr, which is also a high-energy compound found in the muscle, can help form ATP rapidly as ATP is used. Energy released when PCr splits is used to form ATP from ADP and P. PCr is also in short supply and needs to be replenished if used.



- The lactic acid system cannot be used directly as a source of energy for muscular contraction, but it can help replace ATP rapidly when necessary. If you are exercising at a high intensity level and need to replenish ATP rapidly, the next best source of energy besides PCr is muscle glycogen. To be used for energy, muscle glycogen must be broken down to glucose, which undergoes a series of reactions to eventually form ATP, a process called glycolysis. One of the major factors controlling the metabolic fate of muscle glycogen is the availability of oxygen in the muscle cell. In simple terms, if oxygen is available, a large amount of ATP is formed. This is known as aerobic glycolysis. If inadequate oxygen is available to meet the energy demands of the exercise task or to maintain a high level of aerobic glycolysis, then insufficient ATP is formed, and lactic acid is a by-product of the process to generate more ATP. This is known as anaerobic glycolysis; anaerobic glycolysis is the scientific term for the lactic acid energy system.

  The lactic acid system is used in sport events in which energy production is near maximal for 30–120 seconds, such as a 200- or 800-meter run. Anaerobic capacity is a term often associated with the lactic acid energy system.

- The third system is the oxygen system. It is also known as the aerobic system. Aerobics is a term used by Dr. Kenneth Cooper in 1968. The oxygen system, like the lactic acid system, cannot be used directly as a source of energy for muscle contraction, but it does produce ATP in rather large quantities from other energy sources in the body. Muscle glycogen, liver glycogen, blood glucose, muscle triglycerides, blood FFA and triglycerides, adipose cell triglycerides, and body protein all may be ultimate sources of energy for ATP production and subsequent muscle contraction. To do this, glycogen and fats must be present within the muscle cell or must enter the muscle cell as glucose, FFA, or amino acids. Through a complex series of reactions metabolic by products of carbohydrate, fat, or protein combine with oxygen to produce energy, carbon dioxide, and water. These reactions occur in the energy powerhouse of the cell, the mitochondrion. The whole series of events of oxidative energy production primarily involves aerobic processing of carbohydrates and fats (and small amounts of protein) through the Krebs cycle and the electron transfer system.



Although the rate of ATP production is lower, the major advantage of the oxygen system over the other two energy systems is the production of large amounts of energy in the form of ATP. However, oxygen from the air we breathe must be delivered to the muscle cells deep in the body and enter the mitochondria to be used.

Human Energy Metabolism

Human metabolism represents the sum total of all physical and chemical changes that take place within the body. The transformation of food to energy, the formation of new compounds such as hormones and enzymes, the growth of bone and muscle tissue, the

destruction of body tissues, and a host of other physiological processes are parts of the metabolic process. Metabolism involves two fundamental processes, anabolism and catabolism.

Anabolism is a building-up process, or constructive metabolism. Complex body components are synthesized from the basic nutrients. For the active individual, this may mean an increased muscle mass through weight training or an increased number of cellular enzymes to better use oxygen following endurance-type training. Energy is needed for anabolism to occur.

Catabolism is the tearing-down process. This involves the disintegration of body compounds into their simpler components. The breakdown of muscle glycogen to glucose and eventually CO_2, H_2O, and energy is an example of a catabolic process. The energy released from some catabolic processes is used to support the energy needs of anabolism.

Metabolism is life. It represents human energy. The metabolic rate reflects how rapidly the body is using its energy stores, and this rate can vary tremendously depending upon a number of factors. For all practical purposes, the total daily energy expenditure (TDEE) may be accounted for by three factors: basal energy expenditure, increases due to eating a meal, and physical activity. Basal energy expenditure accounts for the largest component of TDEE, whereas physical activity is the most variable.

Body energy consumption

Occurs by the 5 following ways.

- **Physical exertion or by voluntary movements.**
- **Mental exertion or mind activity.**
- **Physiological functions of the body. (involuntary activity).**
- **Body cellular metabolic and synthetic reactions.**
- **Energy lost by dissipation or nonspecific purposes.**

- **Physical exertion:** This is the way most of the energy of the body is spent in living animal and humans' beings. This is done due to the intention to move, perform or work. This may not be seen in plants as they do not move. The body energy is also consumed for muscle contractions and relaxation. We see this during walking, running, lifting, jumping, talking, shouting etc. Further body language also consumes energy. So, you can notice that when you are hungry your body language will be low and ineffective.
- **Mental exertion:** This is the next way how energy is used in higher animals like humans. Good amount of energy is consumed for thinking, learning, memorizing. Hence during heartbeat, at least 20% of blood pumped from heart goes directly into the brain.This brain is high energy demanding organ, so it requires more glucose and oxygen from blood. Besides, anxiety and other behavior related functions need energy. Hence under stress you can notice eating more will reduce stress. So, Body first tries to fill up this energy need more than other energy needs. Even animals do some sort of brain and behavioral activity but low unlike humans.
- **Physiological functions:** All the physiological functions in the body need energy. These include heart beat, blood flow, breath (inspiration & expiration), digestion, intestinal contractions etc require constant supply of energy. These are involuntary in nature without the intention of the animals. But are always active and energy demanding. The energy is mostly used up due to smooth muscle contractions in gut, blood vessels, lungs. The cardiac muscle in the heart is even more active and highly energy demanding. Also, blood vessel carry blood to corners of the body and bring back by veins by contractions and relaxations.
- **Body metabolic and synthetic reactions:** Most of the body cell reactions like formation of proteins (translation), multiplication of genes, formation of genes demand energy. Also transport of salts, nutrients across the cell membrane, degradation of toxic waste (metabolism) require energy. Further enzymes are

the key factors involved in above reactions. These enzymes perform only at body temperature. So, body tries to maintain heat at a constant by heat generation.

- **Energy lost by dissipation:** The formed is quite valuable but still it is lost. Here the energy is dissipated from the body in the form of heat. Body tries to maintain constant fixed temperature to keep up the physiology. This temperature is generated by burning calories in muscles. During cold weather or atmospheric temperature, the body loses heat. So, you can remember during winter you will feel more hunger and crave for food. Also, energy is lost when material goes out of the body. This we prominently see during breathing, hot air goes out and cool air comes in. Also, to some extent heat is lost by due to urination, bowels evacuation.

How much energy do I need to consume daily?

The amount of energy consumed by a person depends on the person's weight and build. It has been found, however, that the amount of energy consumed by a person during a given activity divided by the surface area of the person's body is approximately the same for most people. Therefore, the energy consumed for various activities is usually quoted in Cal/m^2-hr. This rate is known as the metabolic rate. To obtain the total energy consumption per hour, we multiply the metabolic rate by the surface area of the person. The following empirical formula yields a good estimate for the surface area.

$$\text{Area } (m^2) = 0.202 \times W^{0.425} \times H^{0.725}$$

Here W is the weight of the person in kilograms, and H is the height of the person in meters.

The surface area of a 70-kg man of height 1.55 m is about 1.70 m^2. His metabolic rate at rest is therefore (40 Cal/m^2-hr)×1.70m^2 = 68 Cal/hr, or about 70 Cal/hr. This metabolic rate at rest is called the basal metabolic rate (BMR).

Human Hearing

Unlike the senses of smell or taste, which rely on chemical interactions, hearing is a mechanical process in which the ear converts sound waves entering the ear into electrical signals the brain can understand.

How We Hear?

The ear is quite a piece of engineering; a complex organization of bones, hairs, nerves and cells. It is made up of three main parts, outer (1), middle (2) and inner (3 and 4). To hear naturally, each part of the ear needs to work well.

1.Sounds enter the ear canal

When these sound waves reach the ear, they travel down the ear canal and hit the eardrum, making it vibrate.

2.The ear drum and bones of hearing vibrate

Three tiny bones in the middle ear link the vibrating eardrum to a tiny bone structure in the inner ear called the cochlea.

3.Fluid moves through the inner ear

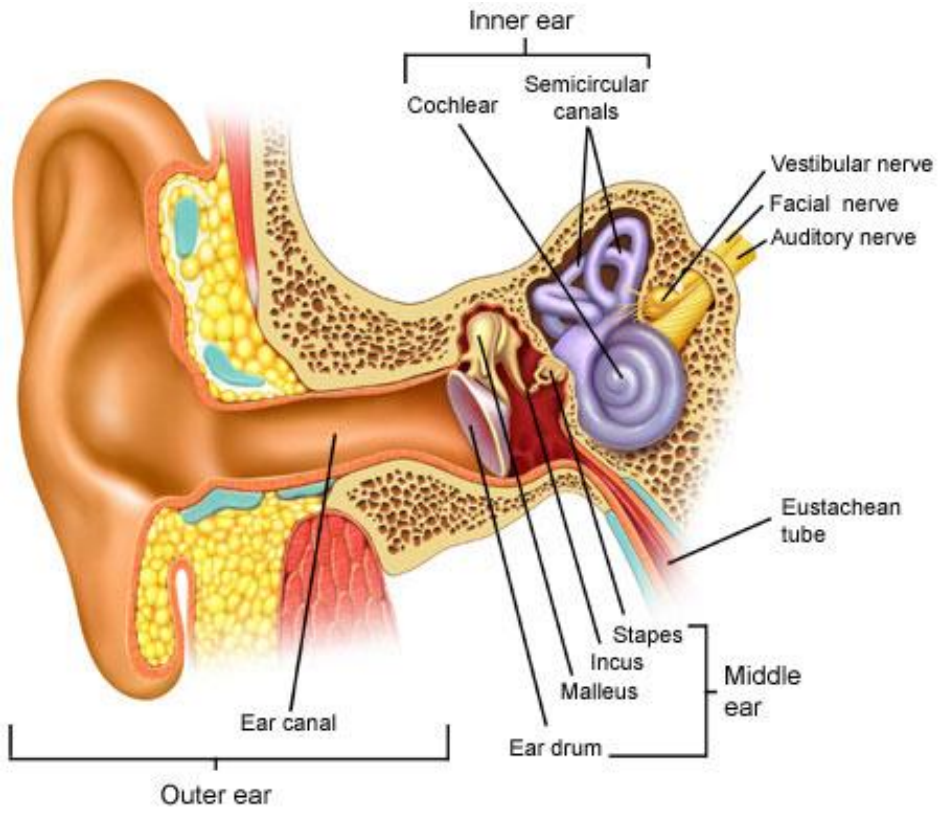
The cochlea is filled with liquid that carries the vibrations to thousands of tiny hair cells.

4.Hearing nerves communicate to the brain

The movement in the fluid causes the cells to carry a message to the nerve that is connected to the brain, which turns the signals into what you hear. The movement in the fluid causes the cells to carry a message to the nerve that is connected to the brain, which turns the signals into what you hear.

To hear the sound traveling through the air, three things have to happen.

1- The sound has to be directed into the hearing part of the ear.
2- The ear has to sense the fluctuations in air pressure.
3- The fluctuations have to be translated into electrical signals that the brain can understand.



Range of Hearing

- The audible range of sound for human beings extends from about 20 Hz to 20000 Hz (one Hz = one cycle/s). Children under the age of five and some animals, such as dogs can hear up to 25 kHz (1 kHz = 1000 Hz). As people grow older their ears become less sensitive to higher frequencies.
- Sounds of frequencies below 20 Hz are called infrasonic sound or infrasound. If we could hear infrasound, we would hear the vibrations of a pendulum just as we hear the vibrations of the wings of a bee. Rhinoceroses communicate using infrasound of frequency as low as 5 Hz. Whales and elephants produce sound in the infrasound range. It is observed that some animals get disturbed before earthquakes. Earthquakes produce low-frequency infrasound before the main shock waves begin which possibly alert the animals.
- Frequencies higher than 20 kHz are called ultrasonic sound or ultrasound. Ultrasound is produced by dolphins, bats and porpoises. Moths of certain families have very sensitive hearing equipment. These moths can hear the high frequency

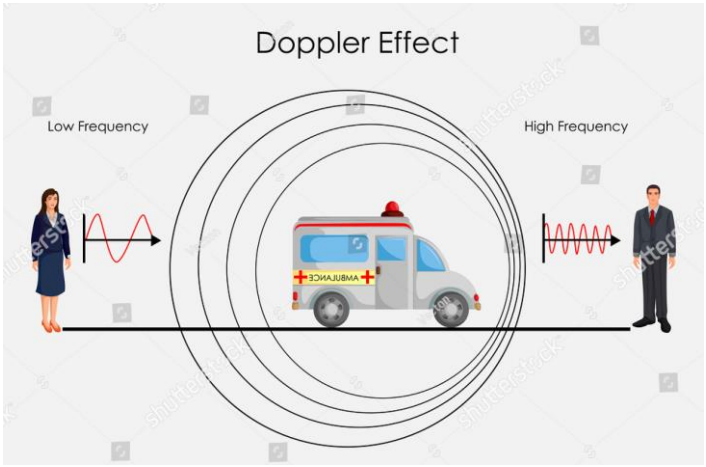
squeaks of the bat and know when a bat is flying nearby and are able to escape capture. Rats also play games by producing ultrasound.

Hearing Aid

People with hearing loss may need a hearing aid. A hearing aid is an electronic, battery operated device. The hearing aid receives sound through a microphone. The microphone converts the sound waves to electrical signals. These electrical signals are amplified by an amplifier. The amplified electrical signals are given to a speaker of the hearing aid. The speaker converts the amplified electrical signal to sound and sends to the ear for clear hearing.

The Doppler effect

The Doppler effect (or the Doppler shift) is the change in frequency or wavelength of a wave for an observer who is moving relative to the wave source. It is named after the Austrian physicist Christian Doppler, who described the phenomenon in 1842. A common example of Doppler shift is the change of pitch heard when a vehicle sounding a horn approach and recedes from an observer. Compared to the emitted frequency, the received frequency is higher during the approach, identical at the instant of passing by, and lower during the recession.



Ultrasound imaging

Ultrasound is sound waves with frequencies higher than the upper audible limit of human hearing. Ultrasound is no different from 'normal' (audible) sound in its physical

properties, except in that humans cannot hear it. This limit varies from person to person and is approximately 20 kilohertz (20,000 hertz) in healthy, young adults. Ultrasound devices operate with frequencies from 20 kHz up to several gigahertz.

Ultrasound is used in many different fields. Ultrasonic devices are used to detect objects and measure distances. Ultrasound imaging or sonography is often used in medicine. In the nondestructive testing of products and structures, ultrasound is used to detect invisible flaws. Industrially, ultrasound is used for cleaning, mixing, and to accelerate chemical processes. Animals such as bats and porpoises use ultrasound for locating prey and obstacles.

From sound to image

The creation of an image from sound is done in three steps – producing a sound wave, receiving echoes, and interpreting those echoes.

1- Producing a sound wave

A sound wave is typically produced by a piezoelectric transducer encased in a plastic housing. Strong, short electrical pulses from the ultrasound machine drive the transducer at the desired frequency. The frequencies can be anywhere between 1 and 18 MHz, though frequencies up to 50–100 megahertz have been used experimentally in a technique known as biomicroscopy in special regions, such as the anterior chamber of the eye.

The sound is focused either by the shape of the transducer, a lens in front of the transducer, or a complex set of control pulses from the ultrasound scanner, in the (beamforming) technique. This focusing produces an arc-shaped sound wave from the face of the transducer. The wave travels into the body and comes into focus at a desired depth.

Materials on the face of the transducer enable the sound to be transmitted efficiently into the body (often a rubbery coating, a form of impedance matching). In addition, a water-based gel is placed between the patient's skin and the probe.

The sound wave is partially reflected from the layers between different tissues or scattered from smaller structures. Specifically, sound is reflected anywhere where there are acoustic impedance changes in the body: e.g. blood cells in blood plasma, small structures in organs, etc. Some of the reflections return to the transducer.

2- Receiving the echoes

The return of the sound wave to the transducer results in the same process as sending the sound wave, except in reverse. The returned sound wave vibrates the transducer and the transducer turns the vibrations into electrical pulses that travel to the ultrasonic scanner where they are processed and transformed into a digital image.

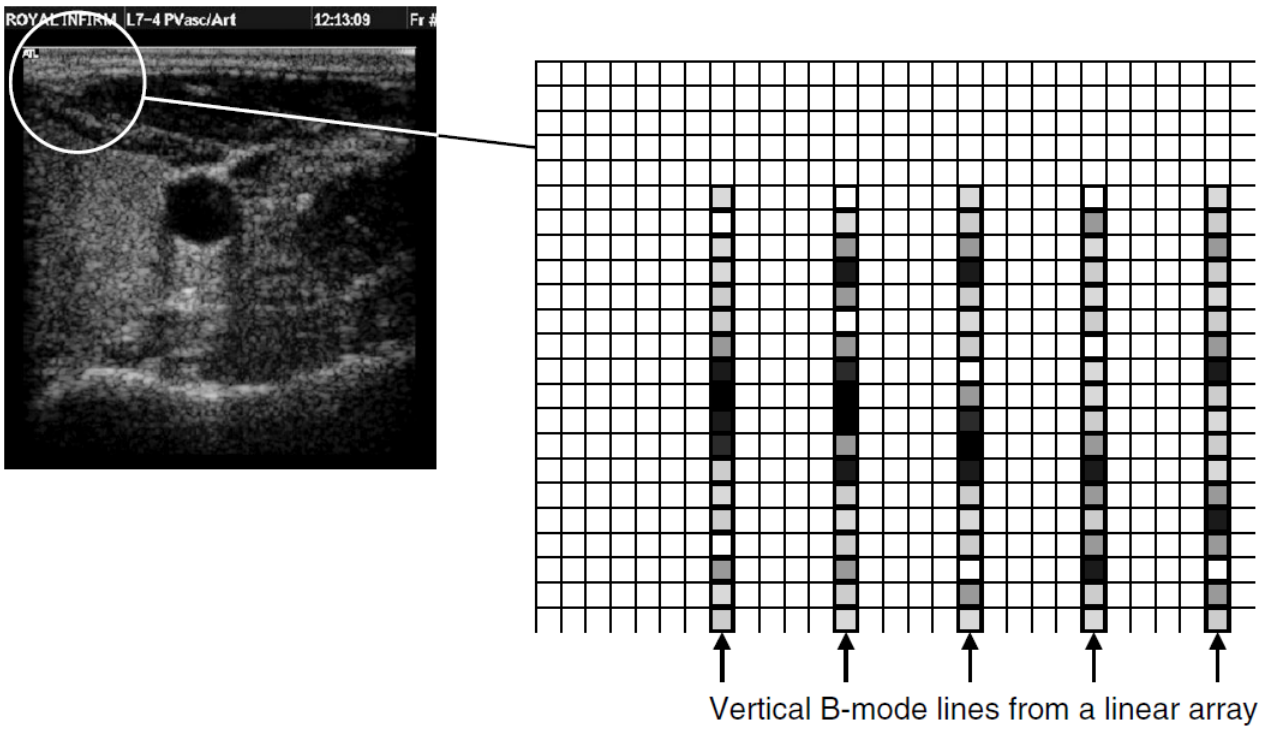
3- Forming the image

To make an image, the ultrasound scanner must determine two things from each received echo:

- **How long it took the echo to be received from when the sound was transmitted.**
- **How strong the echo was?**

Once the ultrasonic scanner determines these two things, it can locate which pixel in the image to light up and to what intensity.

Transforming the received signal into a digital image may be explained by using a blank spreadsheet as an analogy. First picture a long, flat transducer at the top of the sheet. Send pulses down the 'columns' of the spreadsheet (A, B, C, etc.). Listen at each column for any return echoes. When an echo is heard, note how long it took for the echo to return. The longer the wait, the deeper the row (1,2,3, etc.). The strength of the echo determines the brightness setting for that cell (white for a strong echo, black for a weak echo, and varying shades of grey for everything in between.) When all the echoes are recorded on the sheet, we have a greyscale image.



Ultrasound Transducer

Ultrasound is generated by a transducer which contains one or more crystals composed of ceramic or naturally occurring piezoelectric materials. Such an example is quartz which following exposure to an applied voltage will provide a consistent mechanical vibration of 32.768 kHz. A quartz crystal commonly provides the fundamental timing element for watches.

Examples of synthetic piezoelectric materials include ceramics such as lead-zirconate-titanate (PZT) or plastic composites such as polyvinylidene difluoride (PVDF).

The piezoelectric material converts an electrical pulse from the ultrasound machine's pulse generator into acoustic energy which can be transmitted for imaging. The electrical pulse induces a change in shape of the piezoelectric material. The expansion and contraction of the piezoelectric material propagates an acoustic wave with compression and rarefaction of a pressure amplitude front. Following interaction of the transmitted pulse with tissue, the transducer will function as a receiver and will detect the returning echoes. The returning acoustic energy deforms the piezoelectric material and generates a sequence of electric signals which are transferred to the ultrasound unit

to help create a medical image. An ultrasound transducer can be used in both pulsed and continuous wave mode.

Types of Transducers

Modern-day medical transducers consist of either linear or curvilinear arrays composed of many rectangular piezoelectric elements. Within the transducer, there may be anywhere from 128 to 512 piezoelectric elements. Based upon the activation mode of how the ultrasound pulse is generated, transducers can be divided into two different types: (1) linear array and (2) phased array.

1- Linear Array

Within a linear array transducer, there is simultaneous activation of a small group of piezoelectric elements. A linear array has all the piezoelectric crystals set in a line across the transducer face.

This produces a rectangular ultrasound image and is usually used for:

- **vessels**
- **vascular access**
- **needle guidance**
- **musculoskeletal imaging**
- **small parts such as breast and thyroid**
- **foreign bodies**

Anywhere we need a wide ‘near field’ but not a lot of depth as linear transducers tend to be higher in frequency than curved arrays.

2- Phased Array

In contrast to a linear array, a phased array transducer produces a single ultrasound pulse from all of the transducer piezoelectric elements. With a phased array, a time delay is introduced in the process of activating the piezoelectric elements across the face of the transducer. Through the introduction of this time delay, the ultrasound pulse can be directed without moving the transducer at all. When the phased array listens for the returning echoes, all of the transducer elements are recruited, and the aggregate information from all of these elements is used to generate an image.

This type of transducer is usually used for:

- **cardiac imaging**
- **difficult or deep intercostal views of the abdomen**
- **sometimes for neonatal head imaging.**

3- A curved array

A curved array is a transducer where the crystals are arranged along a curved surface, this produces a wide near field, and a wide far field. This produces an image with a curved upper and lower edge.

This type of transducer is usually used for:

- **abdominal**
- **obstetric**
- **gynecology**

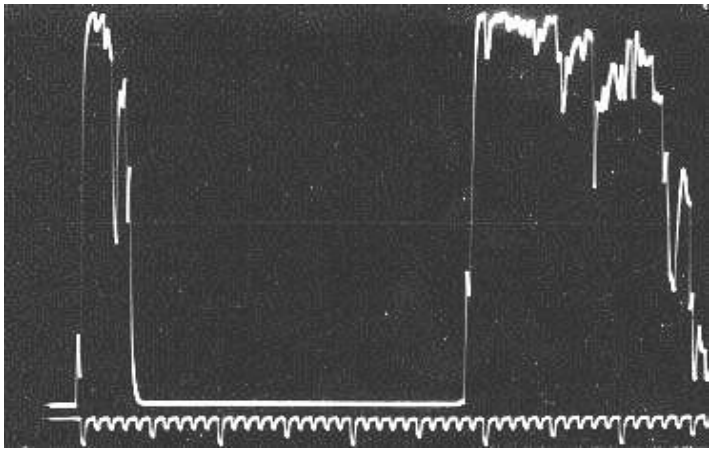
Anywhere we need a lower frequency and good depth penetration. the curved array transducer may be used if we are attempting to visualize difficult or deep vessels in abdomen, leg or upper body.

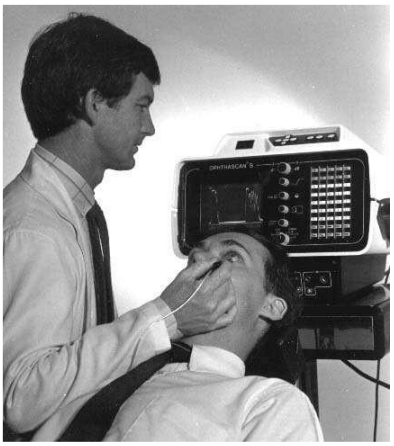
Types of Echo Display

The returning echo to the transducer can be displayed in one of three different ways: A-mode, B-mode, and M-mode.

1- A-Mode

A-mode represented the first type of ultrasound display and stands for amplitude mode.



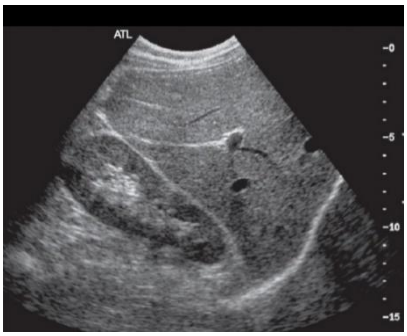


Echo amplitude was displayed on the vertical axis, while echo return time was displayed on the horizontal axis.

As described earlier, *echo return time is an indication of depth or distance of a tissue interface from the transducer*. One A-line of data was generated for each pulse repetition period. Initially, A-mode was used to evaluate midline displacement of the brain in patients suffering from a brain tumor. Today, A-mode can be used by ophthalmologists (eye doctors) for precise measurements of the eye.

2- B-Mode

B-mode displays a grayscale image of a tissue section and stands for brightness mode. The greater the intensity of the returning echo, then the greater the displayed signal brightness or level of echogenicity.



The returned echoes are displayed as a function of depth from the transducer and position across the sector scan of the emitted ultrasound beam.

Essentially, one 2D B-mode image is generated by a number of A-lines spanning across the transducer's field of view.

3- M-Mode

This technique stands for motion mode. This imaging approach uses the signal from B-mode imaging to describe the echoes of a moving structure such as the heart with the transducer oriented on a fixed position or tissue interface within the patient.

M-mode displays depth on the vertical axis and time on the horizontal axis.

By displaying successive ultrasound pulses next to each other, the change in the position of a single tissue interface can be monitored, and M-mode can be used to illustrate time-dependent motion. This display technique can be used to focus on the tissue interface of a beating heart and to help estimate the heart rate of a 6-week live fetus. M-mode can only focus on the motion of a single tissue interface or line through the patient. Given this limitation and advancements in two-dimensional echocardiography, this technique has been largely replaced by color Doppler imaging.

Components of an Ultrasound Machine

For the pulse echo method of ultrasound image acquisition, several hardware components are needed within the ultrasound machine including: a beam former, a pulser, a receiver, a scan converter, and a video display.

1- Beam Former

The beam former applies electronic delays to help align the phases of the echoes returning to the many individual elements of an array transducer. The realigned signals from all the transducer elements are then summated, creating an output signal which represents the acoustic information from a pulsed ultrasound beam.

2- Pulsar

The pulsar generates the electric voltage which is applied to the piezoelectric elements within the transducer and produces the acoustic signal.

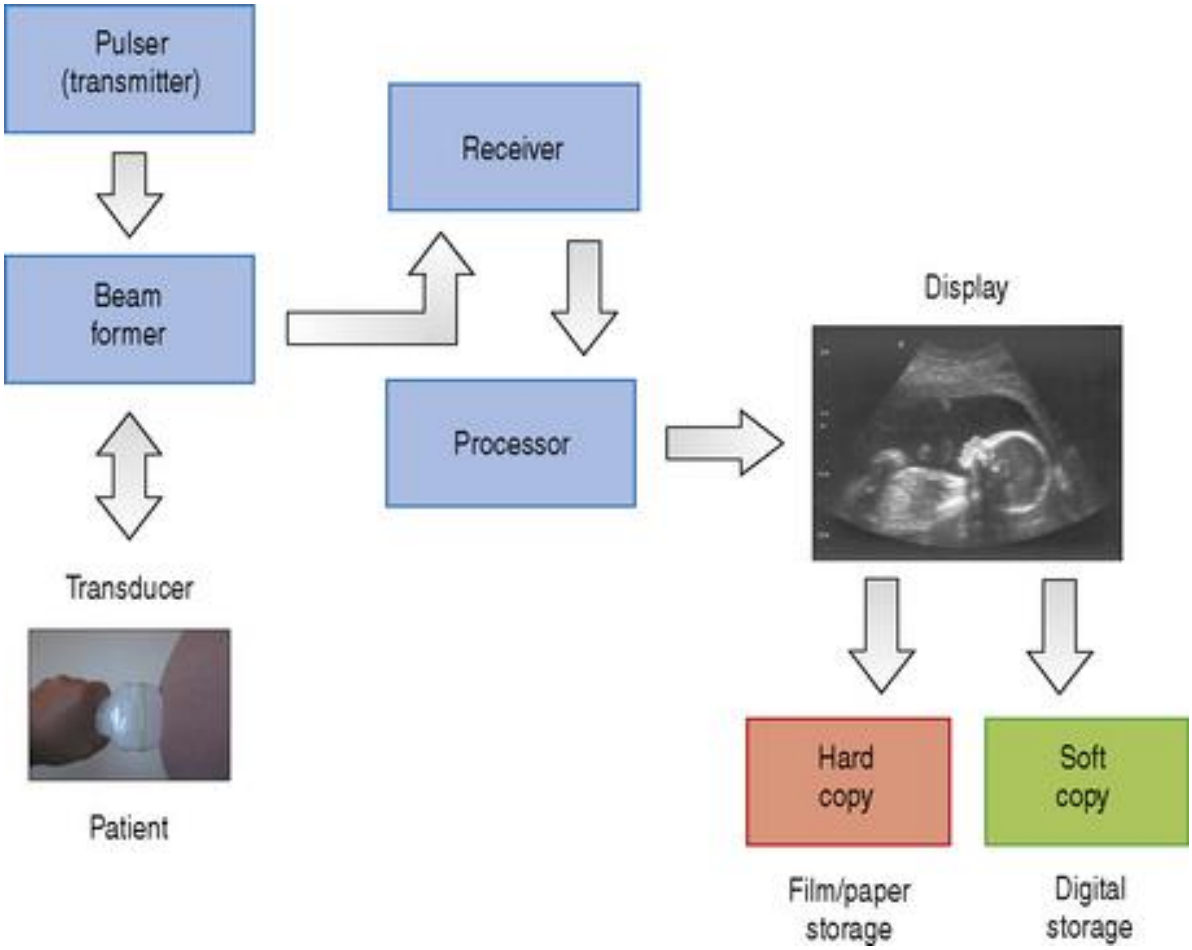
3- Receiver

The receiver accepts signal information from the beam former and performs postprocessing and filtering of noise and clutter.

4- Scan Converter

Scan converter is a device within the ultrasound machine that takes the signal information from the returning echo and translates it into a data format which can be displayed as a 2D image. The data format from scan acquisition and scan display are very different, and the scan converter is a critical hardware piece for a functional ultrasound machine to display a medical image that can be read by a clinician. Video Display

Once the digital information is acquired and assigned to a memory location, the digital to analog converter converts the matrix of digital data into an analog signal which can be displayed on a video monitor. In addition to the grayscale information from a 2D B-mode image, the video display can show information acquired from M-mode and Doppler ultrasound.



Resolution

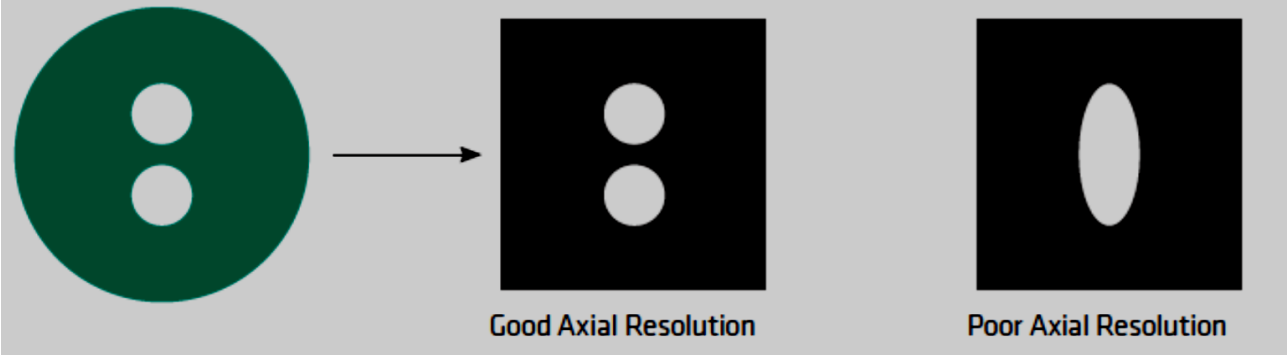
We speak about the resolution of the image – what this term means is 'how well we can distinguish the structures we need to see'. There are different types of resolution – Temporal, Contrast and Spatial:

Temporal Resolution – how accurately we demonstrate a moving structure over time – this is important in Echocardiography and Obstetric scanning.

Contrast Resolution – how well the system displays structures with differing reflection characteristics as different shades of grey in the image.

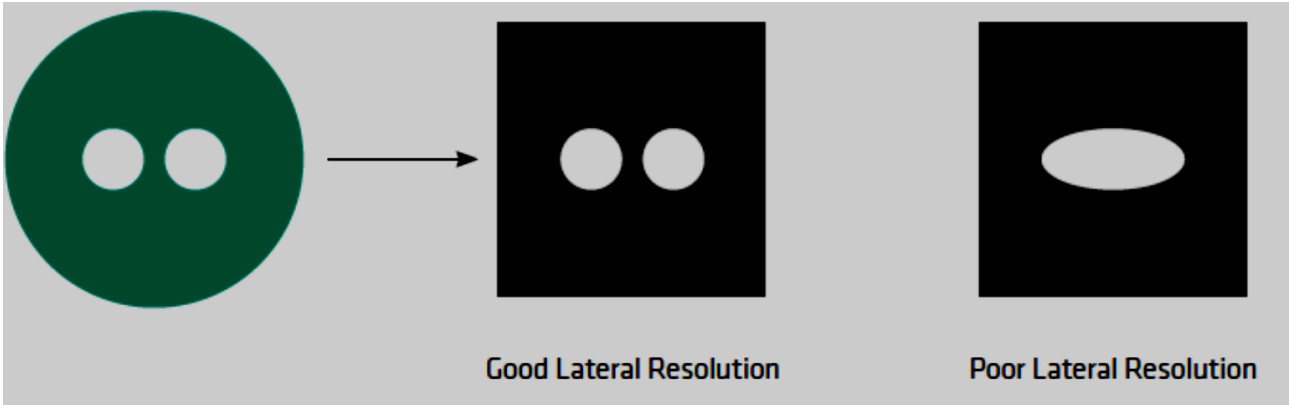
Spatial Resolution – can be divided into two different types:

Axial Resolution is the ability of the system to display small structures along the axis of the beam as separate from each other (parallel to the beam) – If we have two small vessels one above the other it is important to see them separately on the image – not as if they were joined or smeared together.



Lateral Resolution is the ability of the system to display small structures side-by-side (same depth) as separate from each other (perpendicular to the beam).

(Lateral Resolution is usually poorer than axial resolution due to the beam width).

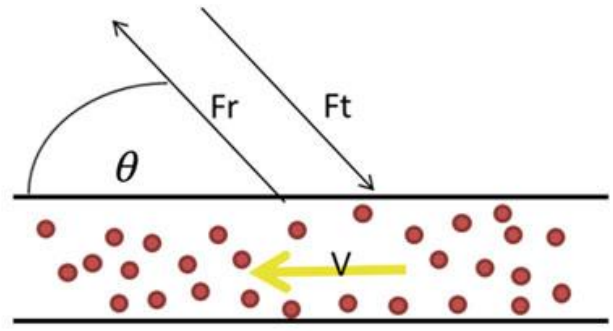


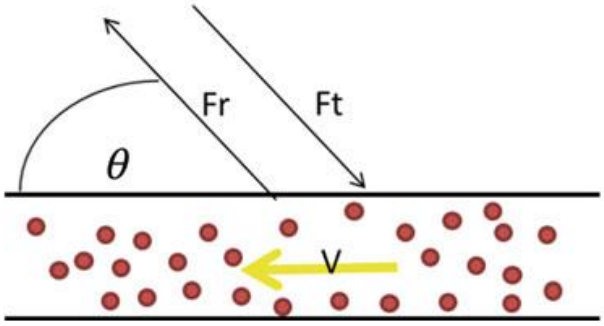
Doppler Ultrasound

Up to this point, discussion has focused upon the generation of grayscale ultrasound imaging. These grayscale images are composed from pressure amplitude information regarding returning echoes which have either been reflected or scattered. Additional imaging information can also be found in the frequency variation of the returning echoes. This detection of a change in echo frequency serves as the basis for Doppler ultrasound imaging.

Frequency shift occurs when incident sound energy reflects off a moving object. If the object is moving away from the source of sound, the returning echo travels at a lower frequency than the initial incident sound, while if the object is moving toward the source of sound, the returning echoes travel at a higher frequency than the initial incident sound. The Doppler frequency shift (F_d) is defined as the difference in frequency between the initial incident sound (F_t) and the returning echo (F_r).

$$F_d = F_t - F_r$$





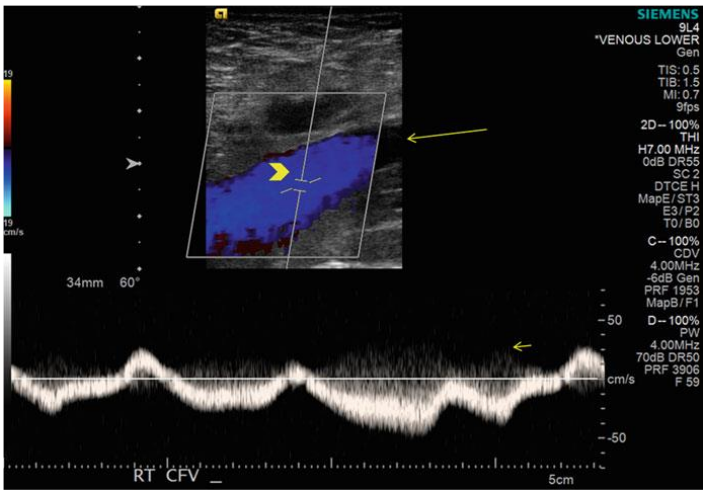
Optimal imaging is performed with the transducer as close as parallel to the vessel of interest so that the cos (θ) is maximized. The velocity (V) is directly proportional to

frequency shift. For Doppler ultrasound imaging, the moving object is usually a red blood cell in either a vein or artery. When the sound hits the moving red blood cell, the incident energy is both reflected and scattered. When the transducer detects the returning echo, the change in frequency can be used to measure the velocity of the blood. In addition, detailed color maps can be generated which outline the anatomy of the vasculature tree and potentially highlight such disease processes as atherosclerotic disease or plaque formation along the vessel wall.

We have introduced two different concepts in this discussion, blood flow and blood velocity. Blood velocity measures the rate that a particle of interest, i.e., a red blood cell, travels per unit time. Blood velocity is measured in cm/sec. Blood flow measures the volume of blood that travels per unit time and is measured in cm^3/sec. Under conditions of fully developed, steady-state flow, the blood flow is related to the mean velocity by the following equation:

$$\text{Flow} = V * A$$

where V is the mean velocity and A is the cross-sectional area of the vessel.



Pulsed Doppler imaging can evaluate both velocity and range (or the distance from where the moving object originates). The transducer obtains information from a specific location of interest or the Doppler sample volume. The size of the Doppler sample volume can be changed by adjusting the amount of time that the transducer receives or listens for returning echoes. By first imaging with grayscale ultrasound imaging, the vessels of interest can be visualized, and the Doppler sample volume can

be positioned within the lumen of the vessel which will be evaluated. Duplex scanning is defined as this combined use of both grayscale and pulsed Doppler imaging. The velocity is represented on the vertical scale, while time is indicated on the horizontal scale. When flow is toward the transducer, this results in a positive frequency shift and a positive magnitude velocity value, while the opposite relation holds true for flow away from the transducer. Generally, flow toward the ultrasound transducer is color-coded as red, while flow away from the transducer is color-coded as blue.

Risks and side-effects

Ultrasonography is generally considered safe imaging with the World Health Organizations saying.

"Diagnostic ultrasound is recognized as a safe, effective, and highly flexible imaging modality capable of providing clinically relevant information about most parts of the body in a rapid and cost-effective fashion".

Diagnostic ultrasound studies of the fetus are generally considered to be safe during pregnancy. This diagnostic procedure should be performed only when there is a valid medical indication, and the lowest possible ultrasonic exposure setting should be used to gain the necessary diagnostic information under the "as low as reasonably practicable" or ALARP principle.

The human eye as an optical refracting system

Interesting facts about eyes that you probably didn't know

- Your eyes are about 2.5 cm across and weigh about 7.087381 gm.
- The human eye can differentiate approximately 10 million different colors.
- Our eyes remain the same size throughout life, whereas our nose and ears never stop growing.
- The human eye blinks an average of 4,200,000 times a year.
- Eyes are made up of over 2 million working parts.
- Each individual eye contains 107 million cells, and all are light sensitive.
- Your eye is the fastest muscle in your body. Hence, the phrase: "In the blink of an eye."
- The world's most common eye color is brown.
- Brown eyes are blue eyes underneath. Consequently, a person can receive surgery in order to make their brown eyes blue.

The eye is an optical instrument that can

- Focus automatically on objects over a wide range of distances
- Adjust automatically to a wide range of light intensities
- Sensitive to a continuous range of electromagnetic waves from less than 400 nm to about 650 nm in wavelength.

The structure the human eye

1. Tear Layer

The Tear Layer (The Lacrimal System) is the first layer of the eye that light strikes. It is clear, moist, and salty. Its purpose is to keep the eye smooth and moist.

2. Cornea

The Cornea is the second structure that light strikes. It is the clear, transparent front part of the eye that covers the iris, pupil and anterior chamber and provides most of an eye's optical power. It needs to be smooth, round, clear, and tough. It is like a protective window.

The function of the cornea is to let light rays enter the eye and converge the light rays.

3. Anterior Chamber

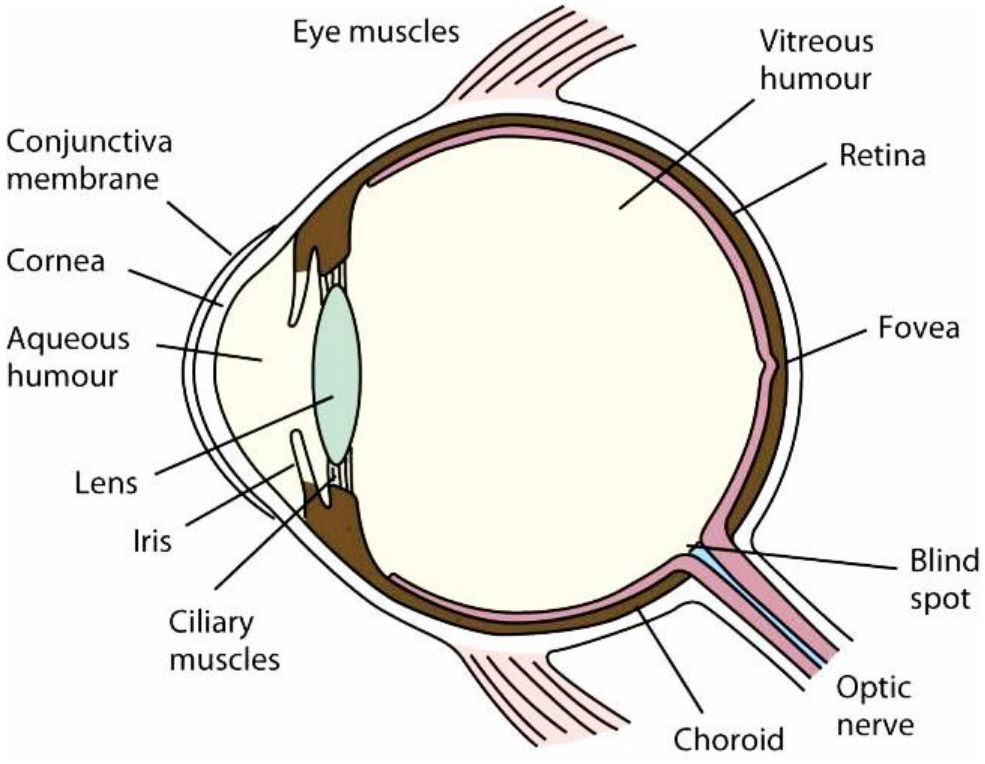
The Anterior Chamber is filled with **Aqueous Humor**. Aqueous Humour is a clear, watery fluid that fills the space between the back surface of the cornea and the front surface of the vitreous, bathing the lens. The eye receives oxygen through the aqueous. **Its function is to feed the cornea, iris, and lens by carrying nutrients. It removes waste products excreted from the lens, and maintain intraocular pressure and thus maintains the shape of the eye.**

4. Iris

The iris is the pigmented tissue lying behind the cornea that gives color to the eye and controls the amount of light entering the eye by varying the size of the papillary opening.

It functions like a camera. The color of the iris affects how much light gets in.

The iris controls light constantly, adapts to lighting changes, and is responsible for near point reading (to see close, pupils must constrict)



Pupil

It is a variable-sized black circular opening in the center of the iris that regulates the amount of light that enters the eye. The pupil needs to be round in order to constrict.

A constricted pupil occurs when the pupil size is reduced to constriction of the iris or relaxation of the iris dilator muscle. The iris constricts with bright illumination, with certain drugs, and can be a consequence of ocular inflammation.

A dilated pupil is an enlarged pupil, resulting from contraction of the dilator muscle or relaxation of the iris sphincter. It occurs normally in dim illumination or may be produced by certain drugs (mydriatics) or result from blunt trauma.

5. Lens

The lens is the natural lens of the eye (crystalline lens). Transparent, biconvex intraocular tissue that helps bring rays of light to focus on the retina (It bends light, but not as much as the cornea).

Ciliary Body. The circumferential tissue (a ring of tissue between the end of the choroids and the beginning of the iris) inside the eye composed of the ciliary muscle (involved in lens accommodation and control of intraocular pressure and thus the shape of the lens) and 70 ciliary processes that produce aqueous fluid.

6. Vitreous Humour (Chamber)

Vitreous Humour (Chamber) is the transparent, colorless gelatinous mass that fills rear two-thirds of the eyeball, between the lens and the retina. It has to be clear so light can pass through it and it has to be there, or eye would collapse.

7. Retina

The retina is the **light sensitive nerve tissue** in the eye that converts images from the eye's optical system into electrical impulses that are sent along the optic nerve to the brain, to interpret as vision.

- **Cones** The cones are the light-sensitive retinal receptor cell that **provides the sharp visual acuity** (**detail vision**) and color discrimination; most numerous in macular area. Function under bright lighting.

- **Rods** The light-sensitive, specialized retinal receptor cell that works **at low light levels** (**night vision**). The rods function with movement and provide **light/dark contrast**. It makes up peripheral vision.
- **Macula** It is the "**yellow spot**" in the small (3 °) central area of the retina surrounding the fovea. It is the area of acute central vision **(used for reading and discriminating fine detail and color)**. Within this area is the **largest concentration of cones.**
- **Fovea** The fovea is the central pit in the macula that produces the **sharpest vision**. **It contains a high concentration of cones** within the macula and no retinal blood vessels.

8. Choroid

The vascular (major blood vessel), central layer of the eye lying between the retina and sclera. Its function is to provide food to the outer layers of the retina through blood vessels. It is part of the uveal tract.

9. Sclera

The sclera is the opaque, fibrous, tough, protective outer layer of the eye ("**white of the eye**") that is directly continuous with the cornea in front and with the sheath covering the optic nerve behind. **The sclera provides protection.**

10. Optic Nerve

The Optic Nerve is the largest sensory nerve of the eye. It carries impulses for sight from the retina to the brain. Composed of retinal nerve fibers that exit the eyeball through the optic disc, traverse the orbit, pass through the optic foramen into the cranial cavity, where they meet fibers from the other optic nerve at the optic chiasm.

11. Extraocular Muscles

- There are six extraocular muscles in each eye:
- **Rectus Muscles.** There are four Rectus muscles that are responsible for straight movements: **Superior** (upward), **Inferior** (lower), **Lateral** (toward the outside, or away from the nose), and **Medial** (toward the inside, or toward the nose).

- **Oblique Muscles.** There are two Oblique muscles that are responsible for angled movements. The **superior oblique** muscles control angled movements **upward toward the right or left**. **Inferior oblique** muscles control angled movements **downward toward the right or left**.

Mechanism of generating visual signals

- Light rays
- cornea and lens
- retina generates impulses in rods and cones opsin and retinol of photo pigment dissociates
- result in change in opsin structure
- cause membrane permeability changes
- it results p.ds. generated in photoreceptor cells
- action potential in ganglion cells through bipolar cells
- optic nerve
- visual cortex area of brain
- image recognized based on earlier memory and experience.

Sensitivity of the eye

- Rods are sensitive to low levels of light intensity but cannot distinguish between colors.
- Cones are of three types, each sensitive to a different range of wavelengths.

Vision defects

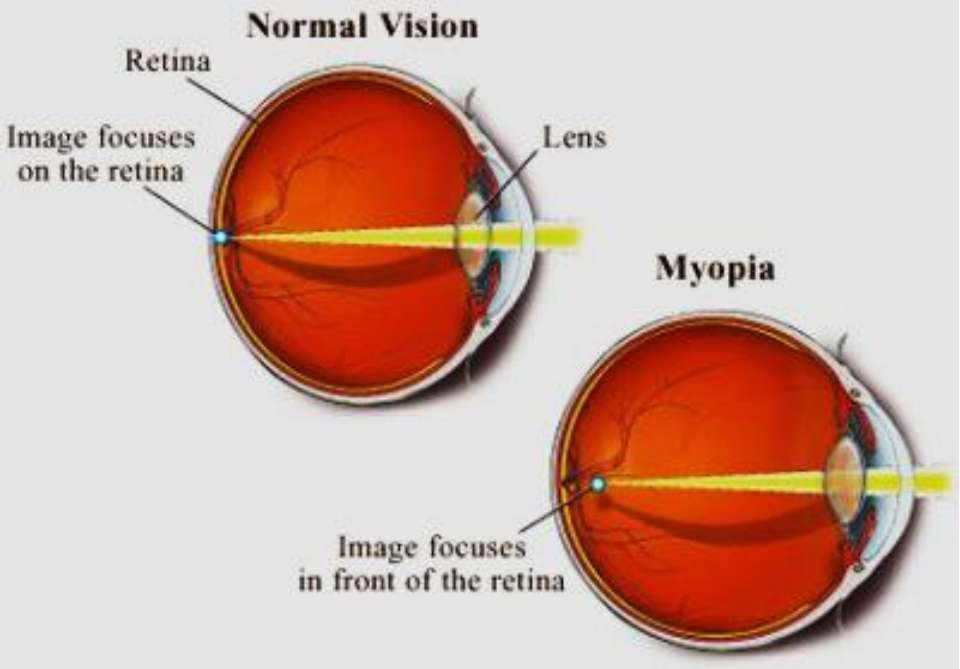
Myopia and hypermetropia

Myopia or short sight

occurs when an eye cannot focus on distant objects. The uncorrected far point of the defective eye is nearer than infinity. This is because the eye muscles cannot make the eye lens thin enough to focus an image on the retina of an object at infinity. The eye can focus nearby objects hence the defect is referred to as ‘short-sight’.

- The cause of myopia is that light, after passing through the eye lens, converges in front of the retina.

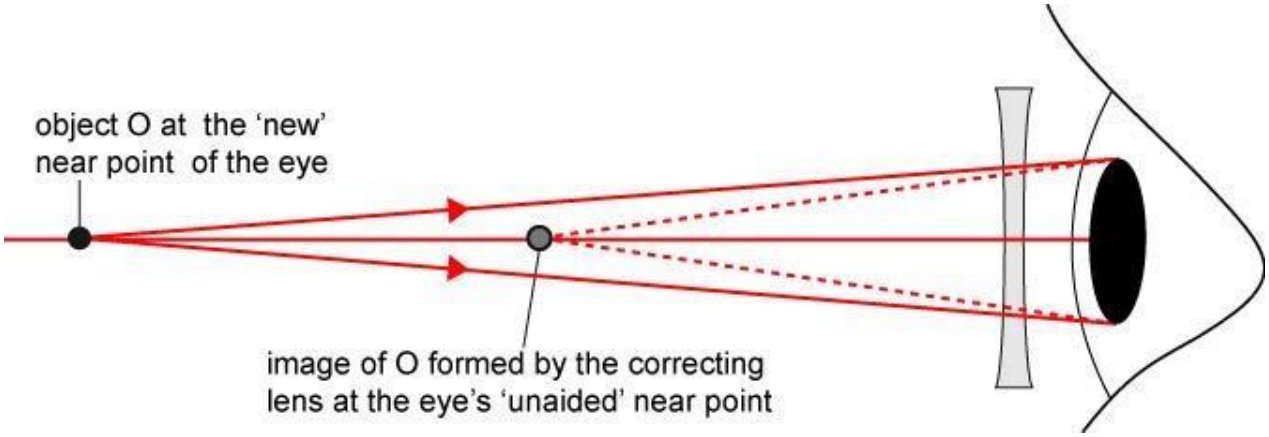
- This happens if the eye lens cannot become thin enough to focus light onto the retina or if the eyeball is too long.



Correction

To correct myopia using a lens, a diverging lens of a suitable focal length must be placed in front of the. The correcting lens makes parallel rays from a distant object diverge so they appear to come from the uncorrected far point. Therefore, the correcting lens for myopia must:

- Be a diverging lens
- Have a focal length equal to the distance from the eye to the uncorrected far point.



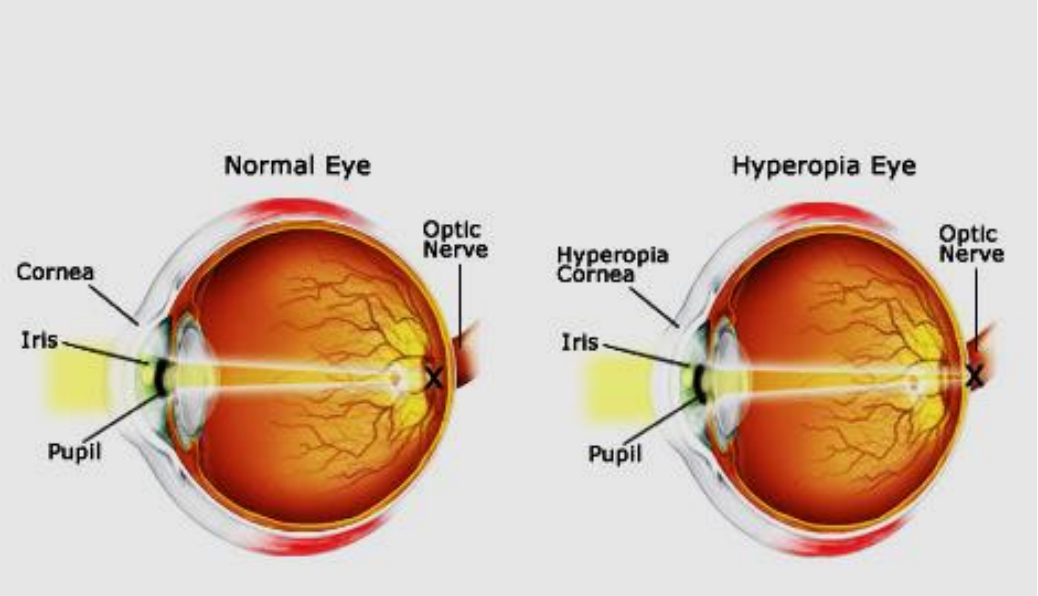
The figure shows that:

- the correcting lens forms a virtual image of the distant point object at the uncorrected far point
- the cornea and eye lens see the object as if it was at the uncorrected far point and form a real image of the object on the retina.

Hypermetropia or long-sight

occurs when an eye cannot focus on nearby objects. The uncorrected near point of the defective eye is further away than 25 cm. This is because the eye muscles cannot make the eye lens thick enough to focus an image on the retina of an object 25 cm away. The eye can focus distant objects hence the defect is referred to as 'long-sight'.

- The cause of hypermetropia is that light, after passing through the eye lens, does not converge enough to form an image on the retina.
- This happens if the eye lens cannot become thick enough to focus light onto the retina or if the eyeball is too short.

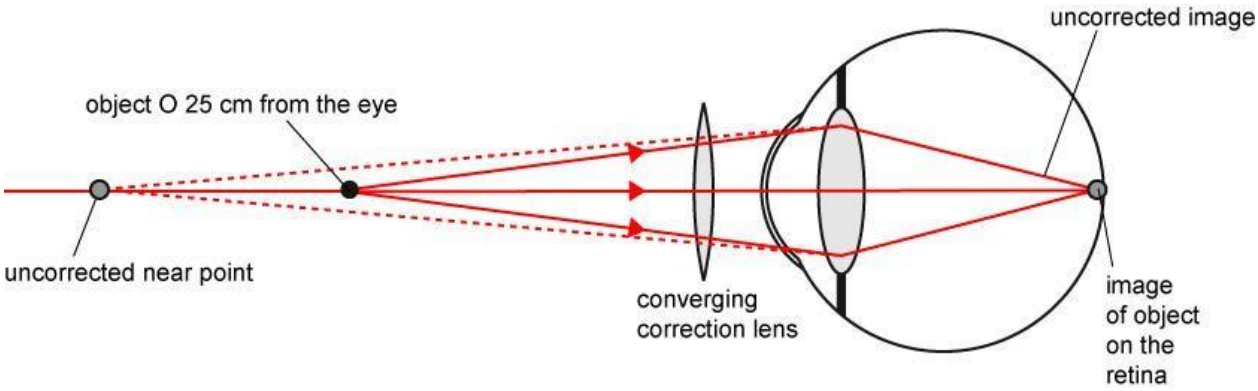


Correction

To correct hypermetropia using a lens, a converging lens of a suitable focal length must be placed in front of the eye. The correcting lens makes the rays from an object 25 cm away diverge less so they appear to come from the uncorrected near point. Therefore, the correcting lens for hypermetropia must:

- Be a converging lens

- Have a focal length which makes an object placed 25 cm from the eye appear as if it is at the uncorrected near point.

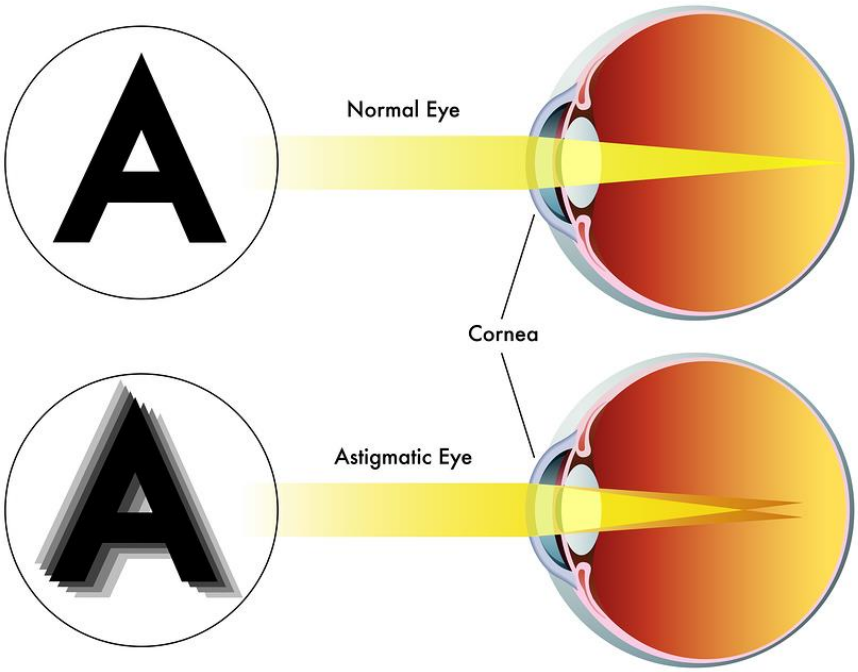


The figure shows that:

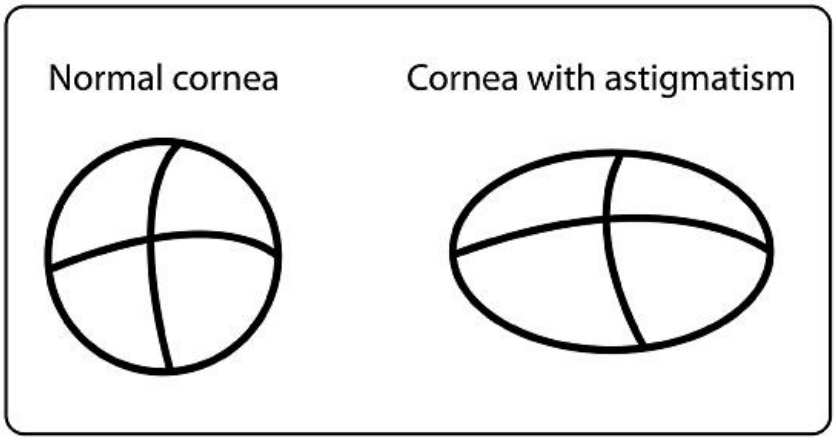
- the correcting lens forms a virtual image of the point object at the uncorrected near point
- the cornea and eye lens see the object as if it was at the uncorrected near point and form a real image of the object on the retina.

Astigmatism

Astigmatism is a sight defect in which objects are seen to be sharper in focus in one direction than in other directions. It is most noticeable when observing parallel lines in perpendicular directions. A simple test for astigmatism is to observe two sets of parallel lines on a card that are perpendicular to each other. If one set of lines stands out more than the other set at a certain orientation (e.g. vertical), the eye is astigmatic. When the card is rotated, the other set of lines stand out more as they reach the same orientation as the first set of lines were in when they were more prominent.



The cause of astigmatism is uneven curvature of the cornea. If the curvature is different in different directions, straight lines at different orientations cannot be focused on the retina at the same time. The more prominent line(s) will be in focus on the retina; the other lines will be out of focus.

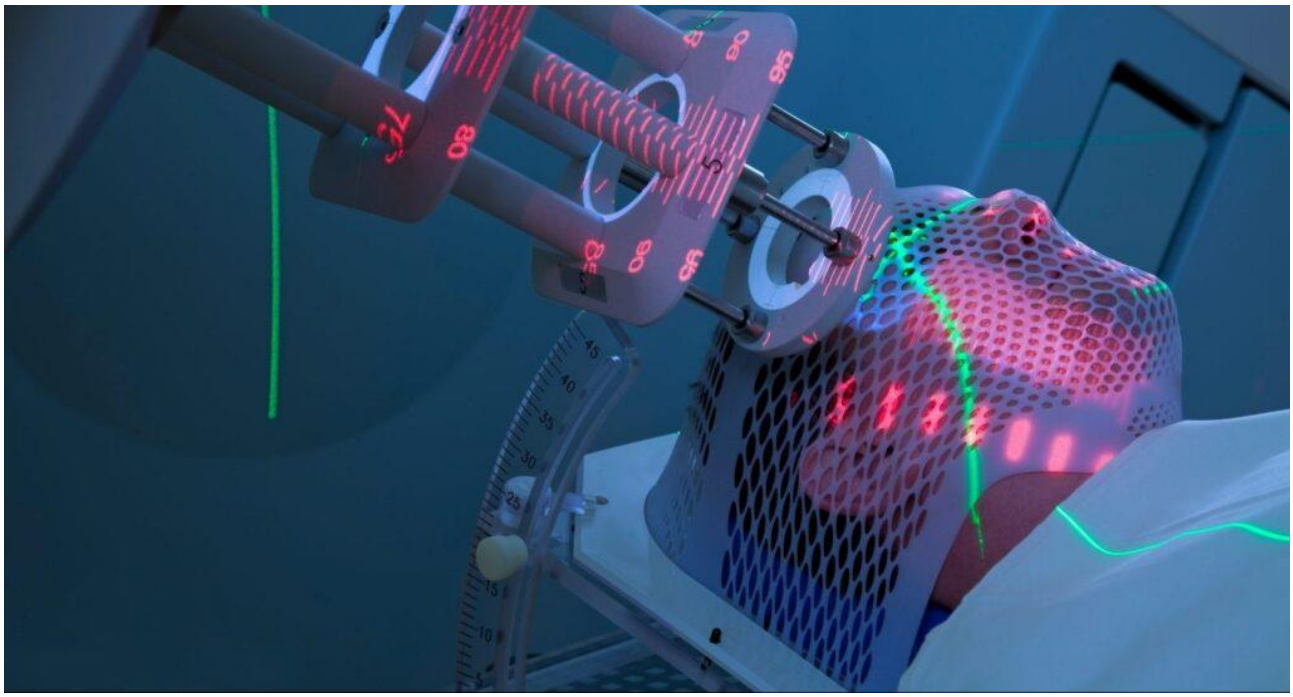


Correction

The correction of astigmatism requires a lens with a cylindrical-shaped surface orientated so that it compensates for the uneven curvature of the cornea. An optician's prescription for astigmatism will state:

- the curvature of the cylindrical-shaped surface
- the orientation of the axis of the cylindrical surface.

Physics of radiation medicine



Classification of Radiation

Radiations are generally classified into two categories: ionizing radiation and non-ionizing radiation. Ionizing radiations are those radiations that can ionize an atom by ejecting one or more orbital electrons from the atom leaving behind a positively charged ion. The energy of ionizing radiation is big enough to overcome the binding energy of the electron in an atom and knock it out.

Alpha (α) rays, beta (β) rays, gamma (γ) rays, and protons are examples of ionizing radiation.

A nucleus or an element that emits these radiations is called parent nucleus or parent element, and the newly produced nucleus as a result of the emission of radiation is called daughter nucleus.

Non-ionizing radiations do not have the ability to knock out an electron from atom to ionize it.

Ultrasound waves and microwaves are examples of non-ionizing radiation.

Ionizing radiations are further divided into two types: directly ionizing radiations and indirectly ionizing radiations.

Directly ionizing radiations are that kind of ionizing radiations that impart their energy to matter directly, through many small electrostatic interactions along the track of the radiation. For example, α-particle, a directly ionizing radiation, ionizes matter directly upon interaction.

Indirectly ionizing radiations are that kind of radiations which first transfer their energy to charged particles in the matter through which they pass. Those charged particles then deliver the energy to the matter. Electromagnetic radiation (x-rays and γ-rays) and neutrons (uncharged particle) transfer their energy to electrons and protons inside matter first followed by the transfer of that energy to matter by those electrons and protons.

Types of Ionizing Radiation

There are different types of ionizing radiation. Everyone has got its distinct characteristic properties and can be used in various applications. These radiations are emitted by unstable nuclei called radioactive nuclei or radioactive material, and the process is called radioactivity.

1- X-Rays

These are electromagnetic radiations emitted as a result of electrons jumping from higher-energy level into lower-energy level in an atom. X-rays emitted as a result of the electronic transitions inside an atom are called characteristic x-rays.

On the other hand, slowing down of a fast-moving electron in an electrostatic field also results in the emission of electromagnetic radiation or x-rays called continuous x-rays or bremsstrahlung radiation. X-rays possess energy, frequency, wavelength, and linear momentum. The energy of an x-ray photon is related to its frequency, wavelength, and momentum by the following equations:

$$E=h\nu \qquad (1)$$

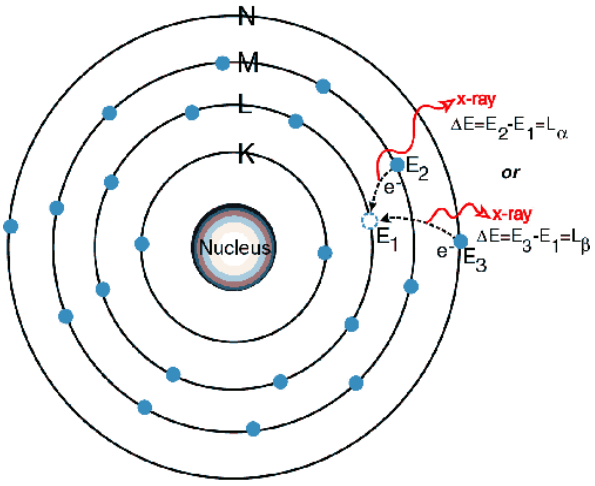
$$E=hc/\lambda \qquad (2)$$

$$E=pc \qquad (3)$$

where "*h*" is the Planck's constant and its value in the International System or SI system is 6.626 x 10^{-34} J.s, *c* is the speed of light in vacuum or free space and its value in SI system is approximately 3 x 10^{8} m/s, ν is the frequency, λ is the wavelength, and "*p*" is the linear momentum of an x-ray photon, respectively. X-rays are highly energetic radiation and could damage normal tissues if exposed. Therefore, in spite of their frequent and wide use in medicine, shielding of normal tissue is mandatory.

In practical applications in medicine, the energy of x-ray is usually given in terms of the generating voltage. The energy ranges of x-rays, in terms of the generating voltage, are given below:

- 0.1–20 kV Low-energy or soft x-rays
- 20–120 kV Diagnostic-range x-rays
- 120–300 kV Orthovoltage x-rays
- 300 kV–1 MV Intermediate-energy x-rays
- 1 MV and above Megavoltage x-rays



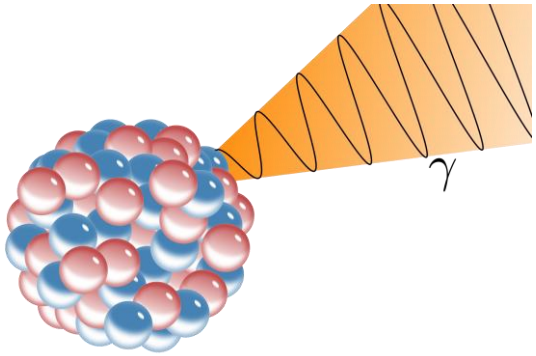
2- γ-Rays

Gamma rays are electromagnetic radiation emitted either from the nucleus of an atom or produced in annihilation process between matter and antimatter (e.g., electron and positron). When a γ-ray emits from the nucleus of an atom, it does not change the mass number or the charge number of the atom. The nature of γ-rays is exactly the same as x-rays. Both are electromagnetic radiation. In the old days, some people were relating

the difference between a γ-ray and an x-ray to their energies and thought γ-rays are more energetic than x-rays. However, this concept is not true.

The difference between the two kinds of radiations is based on their origin. X-rays originate as a result from electronic transitions inside an atom. On the other hand, γ-rays originate from the nucleus of an atom.

It is possible that in some cases, the energy of an x-ray photon may be higher than a γ-ray photon. For example, the energy of a megavoltage x-ray photon is higher than the energy of the highest-energy (1.33 MeV) γ-ray photon emitted from Co^{60}. In calculating energy, frequency, wavelength, or momentum of both kinds of radiation (x-rays and γ-rays), the same equations are used. Radioactive materials emitting γ-rays are widely used in nuclear medicine.



Example

The frequency of a γ-ray photon is 2 x 10^{18} Hertz (Hz). Find the energy, wavelength, and linear momentum of this photon.

Solution

Frequency of the γ-ray photon $\nu = 2 \times 10^{18}$ Hz.

(a) Energy E = ? (b) Wavelength λ = ? (c) Momentum p = ?

(a) Using Eq. (1), $E = h\nu = 6{:}626 \times 10^{-34} \times 2 \times 10^{18} = 1.3252 \times 10^{-15}$ Joule (J)

To write the answer in electron volts,

$$1 \text{ electronvolt (eV)} = 1.6 \times 10^{-19} \text{ J},$$

$$1\text{J} = 1/(1.6 \times 10^{-19}) \text{ eV}.$$

Therefore,

1.3252×10^{-15} J = $(1.3252 \times 10^{-15}) / (1.6 \times 10^{-19})$

$= 8.282 \times 10^{3}$eV

= 8.282 keV

Thus, $E = 1.32 \times 10^{-15}$ J or 8.28 keV

(b) From Eqs. (1) and (2) $E = h\nu = hc/\lambda$

$\lambda = c/\nu$

$=3 \times 10^{8}/2 \times 10^{18} = 1.5 \times 10^{-10}$m

Since 10^{-10} m = 1 A°

Therefore, λ = 1.5 A°

Thus, $\lambda = 1.5 \times 10^{-10}$ m or 1.5 A°

(c) Using Eq. (3)

$E = pc$ Or $p = E/c$

$p = 1.3252 \times 10^{-15} / 3 \times 10^{8}$

$p = 4.42 \times 10^{-24}$ N.s

3- β-Rays

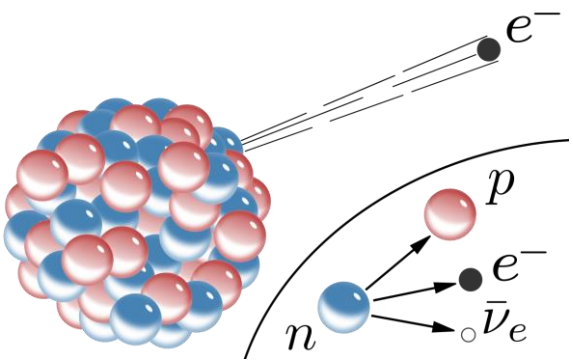
Beta rays are ionizing radiations that originate in the nucleus of an atom. A β-ray is exactly like an electron with the only difference being the separate origins of the two. As mentioned, a β-ray originates from the nucleus of an atom, while an electron resides in an orbit around a nucleus. Beta rays are subdivided into two types: β^- and β^+. β^- has the same charge and mass as possessed by an electron, given as $m_o = 9.109 \times 10^{-31}$ kg and e= -1.6×10^{-19} C. β^+ is like a positron and has the same mass as possessed by an electron but opposite charge. The charge number (Z) and mass number (A) of a β^- are -1 and 0, respectively. β^+ has Z=1 and A = 0. When a β^- is emitted by a nucleus, the charge number of that atom increases by 1 unit, and the mass number remains unaffected according to the following reaction.

$$_{Z}X^{A} \rightarrow {}_{Z+1}Y^{A} + \beta^{-} + \bar{\upsilon}$$

On the other hand, when a β^+ emits from a nucleus, the charge number of the atom decreases by one unit, and the mass number is unaffected. The following reaction describes this information.

$$_{Z}X^{A} \rightarrow {}_{Z-1}Y^{A} + \beta^{+} + \upsilon$$

where additional particles called neutrino (υ) and anti-neutrino ($\bar{\upsilon}$) are also emitted along with beta rays in order to conserve spin in the above reactions.



Example

Radioactive aluminum ($_{13}Al^{28}$) emits β^- and radioactive nitrogen ($_{7}N^{13}$) emits β^+. Show the reactions in both cases and identify the nuclei formed after the emission of these radiations.

Solution

Since the emission of β^- raise the charge number by one unit, but the mass number remains unaffected therefore,

$$_{13}Al^{28} \rightarrow {}_{14}Si^{28} + \beta^{-}$$

Thus, the newly formed nucleus or atom is silicon. In case of β^+ emission, the charge number lowers by one unit, and mass number remains the same, therefore,

$$_{7}N^{13} \rightarrow {}_{6}C^{13} + \beta^{+}$$

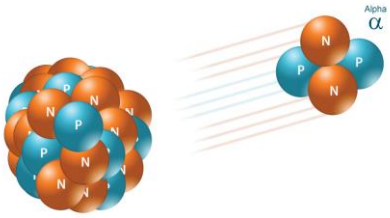
Thus, $_{6}C^{13}$ is the newly formed atom.

4- α-Rays

Alpha rays are ionizing radiations that originate inside the nucleus of a radioactive element. An α-ray has a mass number A =4 and charge number Z = 2. The same mass number and charge number are also possessed by a helium nucleus; therefore, an α-ray is also called a helium nucleus. Therefore, α-ray can also be expressed as $_{2}He^{4}$. Since an α-ray possesses higher charge and mass as compared to a β-ray, therefore its ionizing ability is also greater than the ionizing ability of a β-ray. When emitted from

a nucleus, the charge number and mass number of the atom reduce by 2 and 4, respectively, according to the following reaction:

$$_{Z}X^{A} \rightarrow Z - 2Y^{A-4} + {}_{2}He^{4}\ (\alpha)$$



Example

A radioactive element disintegrates into $_{86}Rn^{222}$ by emitting an α-ray. Find Z and A of the parent nucleus.

Solution

Considering the general reaction for the α-ray emission.

$$_{Z}X^{A} \rightarrow Z - 2Y^{A-4} + {}_{2}He^{4}$$

Since the daughter element is $_{86}Rn^{222}$. Therefore, by comparison

Z - 2 = 86 and A - 4 = 222

Thus Z = 88 and A = 226

Thus the parent nucleus had Z = 88 and A = 226. These Z and A are possessed by radium; therefore, the exact parent nucleus is $_{88}Ra^{226}$.

Radiation units

When an atom disintegrates, radiation is emitted. If the rate of disintegrations is large, the radioactive source is considered to have a high activity. The unit for the activity of a radioactive source was named after Becquerel (abbreviated Bq) and is defined as:

1 Bq = 1 disintegration per sec

In a number of countries, the old unit, the curie (abbreviated Ci and named after Marie and Pierre Curie) is still used. The curie-unit was defined as the *activity in one gram*

of radium. The number of disintegrations per second in one gram of radium is 37 billion. The relation between the curie and the becquerel is given by:

$$\mathbf{1\ Ci = 3.7 \times 10^{10}\ Bq}$$

The accepted practice is to give the activity of a radioactive source in becquerel. This is because Bq is the unit chosen for the system of international units (SI-units). But one problem is that the numbers in becquerel are always very large. Consequently, the activity is given in kilo (10^3), mega (10^6), giga (10^9) and tera (10^{12}) becquerel. If a source is given in curies the number is small.

Radiation Dose

So far, we have discussed the intensity of a radioactive source – i.e. the number of Bq. Radioactive sources represent no biological risk as long as they are isolated from the environments. However, when people (or another biological system) are exposed to radiation – a radiation dose is delivered.

It is therefore important to distinguish between the activity of a radioactive source (measured in becquerels) and the radiation dose which may result from the source. The radiation dose depends on the location of the source with regard to those exposed. Furthermore, the radiation dose depends upon the type of radiation, such as whether it is α-, β- or γ-rays and the energy of the radiation.

Although people can neither see nor feel radiation, it is known that radiation deposits energy to the molecules of the body. The energy is transferred in small quantities for each interaction between the radiation and a molecule and there are usually many such interactions.

For anything that is irradiated, the temperature rises. Additional radiation increases the temperature further. The temperature increase occurs because the radiation energy is transformed into heat. Even though it is generally very difficult to detect the rise in temperature, the realization that heat is generated by radiation is a key element in understanding the concept of *radiation dose.*

Radiation dose measures the amount of energy deposited in an irradiated compound.

Radiation dose is measured in units of gray (Gy)

1 Gy = 1 joule absorbed energy per kg

❖ Roentgen:

Is the measurement of energy produced by Gamma or X -Ray radiation in a cubic centimeter of air. It is abbreviated with the capital "R". One milliroentgen, abbreviated "mR" is one-thousandth of a roentgen. One microroentgen, abbreviated “µR” is one-millionth of a roentgen.

❖ RAD:

Radiation Absorbed Dose. Original measuring unit for expressing the absorption of all types of ionizing radiation (alpha, beta, gamma, neutrons, etc) into any medium. One rad is equivalent to the absorption of 100 ergs of energy per gram of absorbing tissue.

❖ REM:

Roentgen Equivalent Man is a measurement that correlates the dose of any radiation to the biological effect of that radiation. Since not all radiation has the same biological effect, the dosage is multiplied by a "quality factor" (Q). For example, a person receiving a dosage of gamma radiation will suffer much less damage than a person receiving the same dosage from alpha particles, by a factor of three. So alpha particles will cause three times more damage than gamma rays. Therefore, alpha radiation has a quality factor of three. Following is the Q factor for a few radiation types.

Radiation	Quality Factor (Q)
Beta, Gamma and X -rays	**1**
Thermal Neutrons	**3**
Fast n, a, and protons	**10**
Heavy and recoil nuclei	**20**

The difference between the rad and rem is that the rad is a measurement of the radiation absorbed by the material or tissue. The rem is a measurement of the biological effect

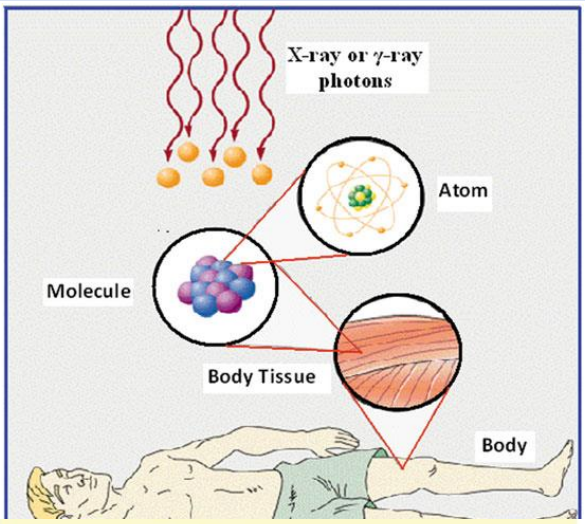
of that absorbed radiation. For general purposes most, physicists agree that the Roentgen, Rad and Rem may be considered equivalent.

❖ System International (SI) Units

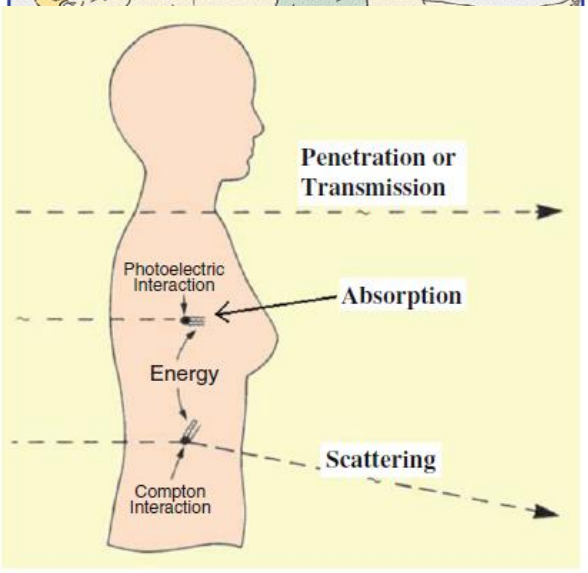
The System International (S.I.) units for radiation measurements are "gray" (Gy) and "sivert" (Sv) for absorbed dose and equivalent dose respectively. The conversion from one system to another is simple:

1 Sv = 100 rem	**1 rem = .01 Sv**
1 mSv = 100 mR (mrem)	**1 mR = .01 mSv**
1 Gy = 100 rad	**1 rad = .01 Gy**
1mGy = 100 mrad	**1 mrad = .01 mGy**

Interaction of Gamma Rays and X-Rays with Matter



Understanding the interaction of X-ray and γ-ray with matter is very important because it is the same interaction that occurs when these radiations come across the human body and tissues. X-ray interactions are important in diagnostic examinations for many reasons. For example, the selective interaction of X-ray photons with the structure of the human body produces the image; the interaction of photons with the receptor converts an X-ray or gamma image into one that can be viewed or recorded. matter including the human body and tissues.



When a γ-ray or X-ray passes through a medium, an interaction occurs between the photons and matter resulting in energy transfer to the medium. The interaction can

result in a large energy transfer or even complete absorption of the photon. However, a photon can be scattered rather than absorbed and retain most of the initial energy while only changing direction. An X-ray or γ-ray photon transfers its energy to the atoms and molecules of the body cells they interact with. As a result, the exposed cells are affected. Those cells take part in the construction of tissues which are also affected by the interaction. The tissues compose the whole body which is eventually affected by the interaction of such X-rays or γ-rays.

Overall when an X-ray beam or gamma radiation passes through an object, three possible fates await each photon:

1. **It can penetrate and transmit the section of matter without interacting.**
2. **It can interact with the matter and be completely absorbed by depositing its energy.**
3. **It can interact and be scattered or deflected from its original direction and deposit part of its energy.**

Types of Interaction with Matter

There are five ways or mechanisms by which photons can interact with matter. Those are photoelectric absorption, Compton scattering, pair production, coherent scattering, and photodisintegration with the first three being the major and most important ways of interaction. All these mechanisms of interaction result in the transfer of energy to the electrons of matter or tissues. The electrons then transfer this energy to matter in many small Coulomb-force interactions. The relative importance of Compton scattering, photoelectric absorption, and pair production depends on both the photon quantum energy and the atomic number of the absorbing medium.

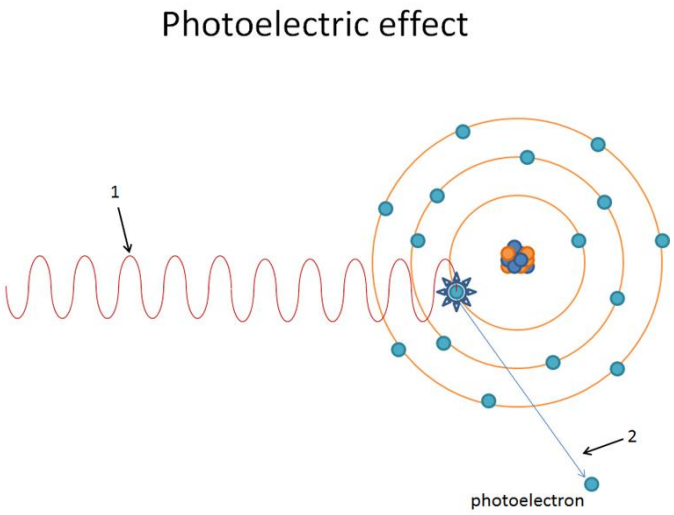
Photoelectric Absorption

The photoelectric absorption or effect is the most important interaction of low energy photons with matter. This effect is dominant in the 0–0.5 MeV photon energy range. Due to its dominancy in low-energy range, this phenomenon plays a major role in radiation dosimetry, diagnostic imaging, and low-energy therapeutic applications. It

has been determined experimentally that when light shines on a metal surface, the surface emits electrons. For example, you can start a current in a circuit just by shining a light on a metal plate. This leads to the explanation of photoelectric effect which can be defined as the phenomenon in which a light photon interacts with a material and gives up all its energy to detach and move out an electron from the surface of the material. The interacting photon gives up its energy completely and is lost. This energy appears in two forms. A part of this energy is utilized to detach or eject an electron. This energy is called work function of the material. The remaining energy of the incident photon is taken away by the electron as its kinetic energy. The ejected electron is called photoelectron.

The following points should be noted about photoelectric absorption:

- A photon, after interaction with an absorber atom, completely disappears.
- In its place, a photoelectron is ejected with its kinetic energy equal to the difference of the absorbed photon's energy and the work function of the absorbing atom.
- For γ-ray or X-ray with sufficient energy, the most probable origin of the photoelectron is the most tightly bound lower shell or the K-shell of the atom.
- The photoelectric interaction is most likely to occur if the energy of the incident photon is just greater than the binding energy of the electron with which it interacts.
- No photoelectric effect will occur if the frequency of the incident photon is smaller than the threshold frequency needed to eject photoelectron.
- No photoelectric absorption will occur if the energy of incident photon is smaller than the work function of the absorbing material.



Compton Scattering

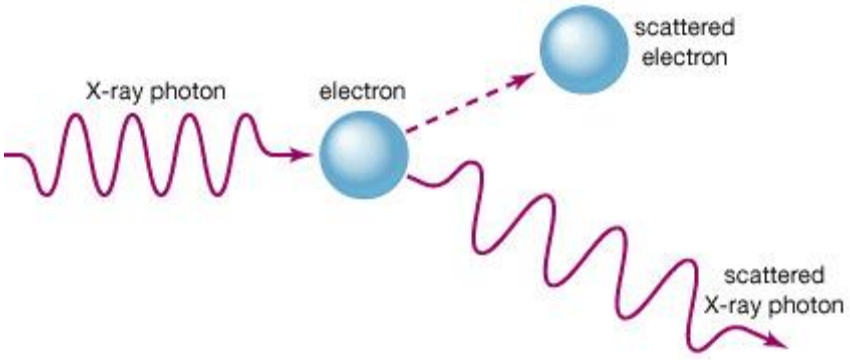
Compton's scattering is the most important interaction in both therapeutic and diagnostic medical physics. For low-Z materials such as air, water, and human tissues, Compton scattering dominantly occurs in approximately 100 keV–30 MeV photon energy range. In high-Z materials, its dominant energy range is 0.5 MeV– 10 MeV. Compton scattering gets special importance in therapeutic medical physics because many of the treatment planning by photon beam are carried out in this energy range. A tumor and normal tissues surrounding the tumor, scatter radiation in various directions, making Compton scattering an important phenomenon to concentrate on.

Compton effect occurs when photons interact with free or weakly bound electrons in the γ-ray incident beam. In this incoherent scattering, all atomic electrons act independently of one another. In Compton scattering, a single photon strikes an electron, giving a part of its energy and momentum to the electron.

This electron is stationary or almost stationary and is called target electron. As a result, the photon scatters with a reduced energy and longer wavelength. The difference in the energy of photon before and after scattering is taken away by the electron as its kinetic energy. This electron is called recoil electron. If a beam of photons is interacting with matter or body tissues, then a number of photons are scattered by the electrons of the atoms that compose the matter or tissues. As a result, the beam attenuation occurs. Moreover, ionization of atoms also occurs as a result of such scattering

The following points should be noted about Compton scattering:

- Compton scattering takes place between the incident gamma ray photon and an electron in the absorbing material.
- It is most often the predominant interaction mechanism for gamma ray energies typical of radioisotope sources.
- It is the most dominant interaction mechanism in tissue.
- The energy transferred to the electron can vary from zero to a large fraction of the gamma ray energy.
- The Compton process is most important for energy absorption for soft tissues in the range from 100 keV to 10 MeV.
- The Compton scattering probability σ decreases as the photon energy increases and is directly proportional to the electronic density of the material.



Pair Production

Pair production is dominant in interactions of higher-energy photons with matter. In this phenomenon, a γ-ray or X-ray photon passing near the nucleus of an atom is subjected to strong field effects from the nucleus and splits into an electron-positron pair. Broadly speaking, a negatively charged electron (e^-) and a positively charged positron (e^+) are created from a photon interacting with the electromagnetic field while energy and momentum are conserved. Positron is a positively charged electron and is created as result of the conservation of momentum when a photon passes near the nucleus of an atom. Since electron (e^-) and positron (e^+) possess particle nature and take part in the construction of matter, therefore, pair production is also called

materialization of energy. The photon should have at least 1.022 MeV or more energy to take part in this process, which is the sum of the rest mass energies of an electron (0.511 MeV) and a positron (0.511 MeV). If the energy of the photon is more than the sum of the rest mass energies of both electron and positron, then the remaining energy is taken by the electron and positron as their kinetic energies, Mathematically

$$h\nu = 1.022\ MeV + KEe^{-} + KEe^{+}$$

where $h\nu$ is the energy of the photon interacting with the nucleus of the atom.

The electron and positron pair do not exist free for long time and recombine through a process called *annihilation* of matter. In the annihilation process, the electron and positron combine with each other, disappear, and give rise to two γ ray photons each with an energy of 0.511 MeV. The two photons move in opposite directions to conserve momentum.

The interaction probability "μ" of a photon with matter by all three processes is simply the sum of each individual probability of occurrence. Mathematically,

$$\mu = \tau + \sigma + \kappa$$

where the interaction probability μ is also called linear attenuation coefficient of a material**.**

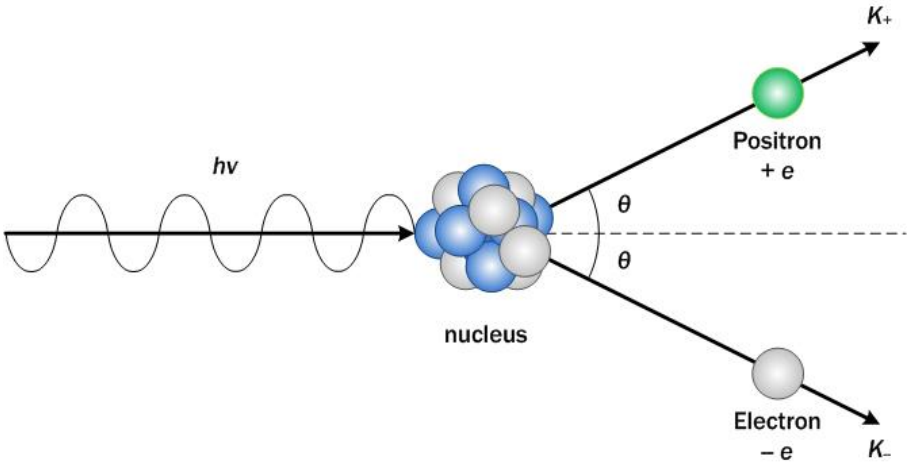
τ is the photoelectric effect interaction probability.

σ is the Compton scattering interaction probability.

κ is the pair production interaction probability.

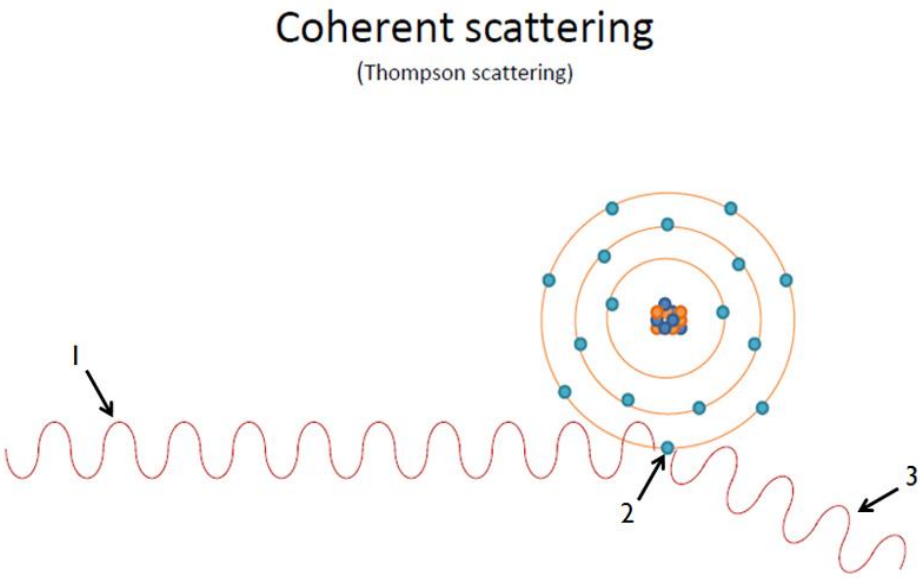
μ is the overall interaction probability.

Along with the major modes of interaction as described above, a photon can also interact with matter through one of the following additional processes though the probability is very little as compared to the three major phenomena.



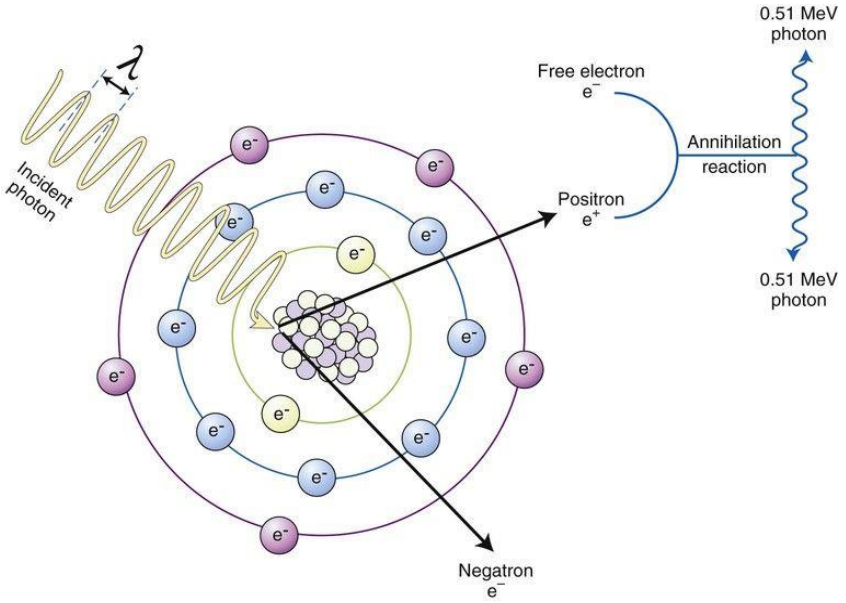
Coherent Scattering

Coherent scattering, often called Rayleigh scattering, involves the scattering of a photon with no energy transfer. Such kind of scattering is also called elastic scattering. The electron is oscillated by the electromagnetic wave from the photon. The electron, in turn, reradiates the energy at the same frequency as the incident wave. The scattered photon has the same wavelength as the incident photon. The only effect is the scattering of the photon at a small angle. This scattering occurs in high atomic number materials and with low-energy photons. In a nutshell, a photon is scattered without losing or gaining any energy.



Photodisintegration

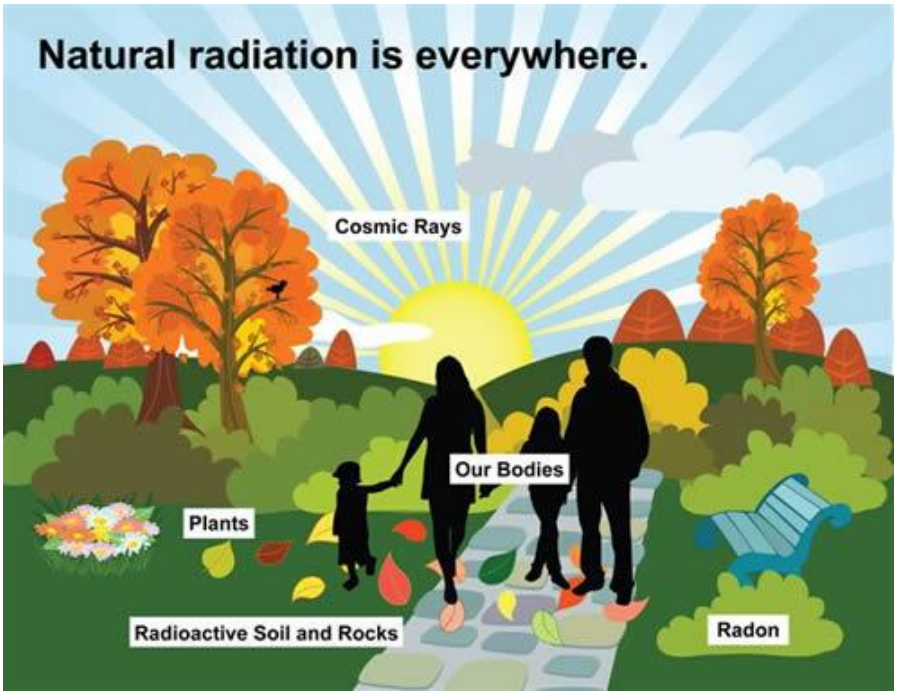
Photodisintegration occurs in high-energy γ-rays at energies over 10 MeV. The γ-ray interacts with the nucleus of an atom, therefore exciting it. The excited nucleus immediately decays into two or more daughter nuclei. A neutron or proton is emitted as a result of this interaction. This is seen in nuclear fission, or the breakdown of an atomic nucleus. The neutrons produced in this reaction can cause radiation protection problems if they are not accounted for.



Radiation Exposure sources

1- Natural background radiation

People are constantly exposed to small amounts of ionizing radiation from the environment as they carry out their normal daily activities; this is known as natural background radiation. Radiation has always been present and is all around us. Life has evolved in a world containing significant levels of ionizing radiation. Our bodies are adapted to it.



2- Exposure from cosmic radiation

The earth's outer atmosphere is continually bombarded by cosmic radiation. Usually, cosmic radiation consists of fast moving particles that exist in space and originate from a variety of sources, including the sun and other celestial events in the universe. Cosmic rays are mostly protons but can be other particles or wave energy. Some ionizing radiation will penetrate the earth's atmosphere and become absorbed by humans, which results in natural radiation exposure.

3- Exposure from soil radiation

The composition of the earth's crust is a major source of natural radiation. The main contributors are natural deposits of uranium, potassium and thorium which, in the process of natural decay, will release small amounts of ionizing radiation. Uranium and thorium are “ubiquitous”, meaning they are found essentially everywhere. Traces of these minerals are also found in building materials so exposure to natural radiation can occur from indoors as well as outdoors.

4- Exposure through inhalation

Most of the variation in exposure to natural radiation results from inhalation of radioactive gases that are produced by radioactive minerals found in soil and bedrock. Radon is an odorless and colorless radioactive gas that is produced by the decay of

uranium. Thoron is a radioactive gas produced by the thorium. Radon and thoron levels vary considerably by location depending on the composition of soil and bedrock. Once released into the air, these gases will normally dilute to harmless levels in the atmosphere but sometimes they become trapped and accumulate inside buildings and are inhaled by occupants.

5- Exposure through ingestion

Trace amounts of radioactive minerals are naturally found in the contents of food and drinking water. For instance, vegetables are typically cultivated in soil and ground water which contains radioactive minerals. Once ingested, these minerals result in internal exposure to natural radiation.

Naturally occurring radioactive isotopes, such as potassium-40 and carbon-14, have the same chemical and biological properties as their non-radioactive isotopes. These radioactive and non-radioactive elements are used in building and maintaining our bodies. Natural radioisotopes continually expose us to radiation.

Artificial sources of radiation

1- Atmospheric testing

The atmospheric testing of atomic weapons from the end of the Second World War until as late as 1980 released radioactive material, called fallout, into the air.

As the fallout settled to the ground, it was incorporated into the environment. Much of the fallout had short half-lives and no longer exists, but some continues to decay to this day. People and the environment receive smaller and smaller doses from the fallout every year.

2- Medical sources

Radiation has many uses in medicine. The most well-known use is X-ray machines, which use radiation to find broken bones and diagnose disease. X-ray machines are regulated by Health Canada and provincial authorities. Another example is nuclear medicine, which uses radioactive isotopes to diagnose and treat diseases such as cancer. These applications of nuclear medicine, as well as the related equipment, are

regulated by the CNSC. The CNSC also licenses those reactors and particle accelerators that produce isotopes destined for medical and industrial applications.

3- Industrial sources

Radiation has a variety of industrial uses that range from nuclear gauges used to build roads to density gauges that measure the flow of material through pipes in factories. It is also used for smoke detectors, some glow-in-the dark exit signs, and to estimate reserves in oil fields. Radiation is also used for sterilization, which is done by using large, heavily shielded irradiators. All these uses are licensed by the CNSC.

4- Nuclear Fuel Cycle

Nuclear power plants (NPPs) use uranium to drive a chain reaction that produces steam, which in turn drives turbines to produce electricity. As part of their normal activities, NPPs release regulated levels of radioactive material which can expose people to low doses of radiation. Similarly, uranium mines, fuel fabrication plants and radioactive waste facilities release some radioactivity that contributes to the dose of the public.

Radiation Exposure Effects

Biological effects of radiation exposure are typically divided into two categories.

The first category consists of exposure to high doses of radiation over short periods of time producing acute or short-term effects.

The second category represents exposure to low doses of radiation over an extended period of time producing chronic or long-term effects.

- **High doses tend to kill cells, while low doses tend to damage or change them.**
- **High doses can kill so many cells that tissues and organs are damaged. This in turn may cause a rapid whole-body response often called the Acute Radiation Syndrome (ARS).**
- **Low doses spread out over long periods of time don't cause an immediate problem to any body organ.**
- **The effects of low doses of radiation occur at the level of the cell, and the results may not be observed for many years.**

Acute radiation dose

An acute radiation dose is defined as a large dose (10 rad or greater, to the whole body) delivered during a short period of time (on the order of a few days at the most). If large enough, it may result in effects which are observable within a period of hours to weeks.

Effects from an acute dose:

Blood-forming organ (Bone marrow) syndrome (>100 rad):

is characterized by damage to cells that divide at the most rapid pace (such as bone marrow, the spleen and lymphatic tissue). Symptoms include internal bleeding, fatigue, bacterial infections, and fever.

Gastrointestinal tract syndrome (>1000 rad):

is characterized by damage to cells that divide less rapidly (such as the linings of the stomach and intestines). Symptoms include nausea, vomiting, diarrhea, dehydration, electrolytic imbalance, loss of digestion ability, bleeding ulcers, and the symptoms of blood-forming organ syndrome.

Central nervous system syndrome (>5000 rad):

is characterized by damage to cells that do not reproduce such as nerve cells. Symptoms include loss of coordination, confusion, coma, convulsions, shock, and the symptoms of the blood forming organ and gastrointestinal tract syndromes.

Other effects from an acute dose include:

- **200 to 300 rad to the skin can result in the reddening of the skin (erythema), similar to a mild sunburn and may result in hair loss due to damage to hair follicles.**
- **125 to 200 rad to the ovaries can result in prolonged or permanent suppression of menstruation in about fifty percent (50%) of women.**
- **600 rad to the ovaries or testicles can result in permanent sterilization.**
- **50 rad to the thyroid gland can result in benign (non-cancerous) tumors.**

Chronic radiation dose

A chronic dose is a relatively small amount of radiation received over a long period of time. The body is better equipped to tolerate a chronic dose than an acute dose. The body has time to repair damage because a smaller percentage of the cells need repair at any given time. The body also has time to replace dead or non-functioning cells with new, healthy cells. This is the type of dose received as occupational exposure.

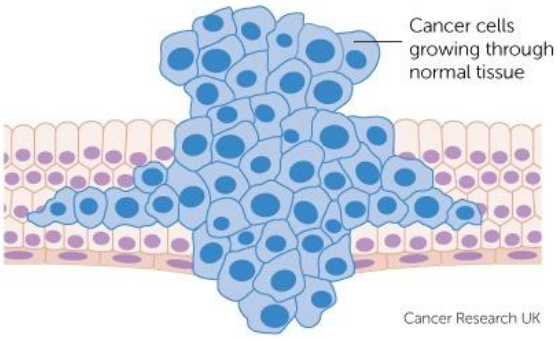
Somatic effects

Somatic effects appear in the exposed person. There is two types of Somatic effects

Prompt somatic effects:

are those that occur soon after an acute dose (typically 10 rad or greater to the whole body in a short period of time). One example of a prompt effect is the temporary hair loss which occurs about three weeks after a dose of 400 rad to the scalp.

Delayed somatic effects:



are those that may occur years after radiation doses are received. Among the delayed effects thus far observed have been an increased potential for the development of cancer and cataracts.

Genetic effects

appear in the future generations of the exposed person as a result of radiation damage to the reproductive cells.

Genetic effects are abnormalities that may occur in the future generations of exposed individuals. They have been extensively studied in plants and animals, but risks for genetic effects in humans are seen to be considerably smaller than the risks for somatic effects. Therefore, the limits used to protect the exposed person from harm are equally effective to protect future generations from harm.

Prenatal radiation exposure

Since an embryo/fetus is especially sensitive to radiation, (embryo/fetus cells are rapidly dividing) special considerations are given to pregnant workers. Protection of the embryo/fetus is important because the embryo/fetus is considered to be at the most radiosensitive stage of human development, particularly in the first 20 weeks of pregnancy.

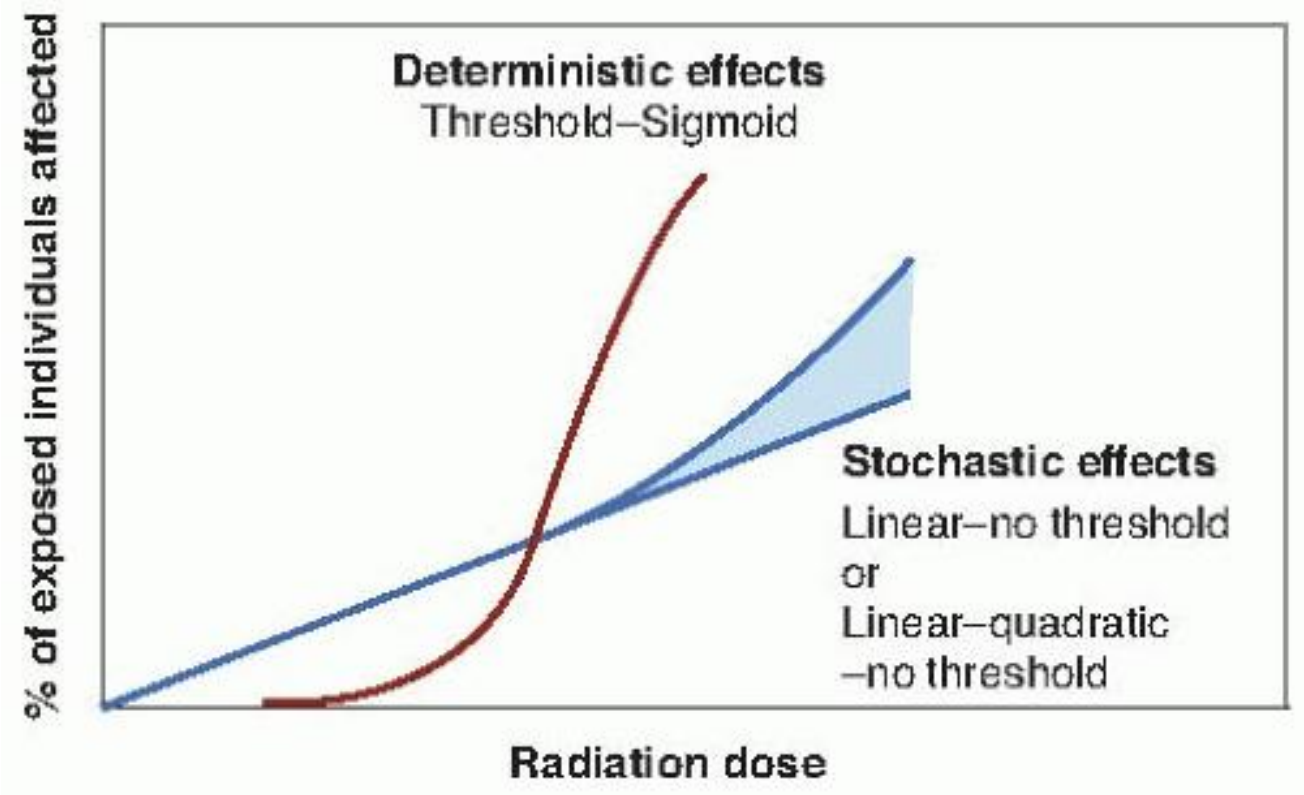
Potential effects associated with prenatal radiation doses include:

- **Growth retardation**
- **Small head/brain size**
- **Mental retardation**
- **Childhood cancer**

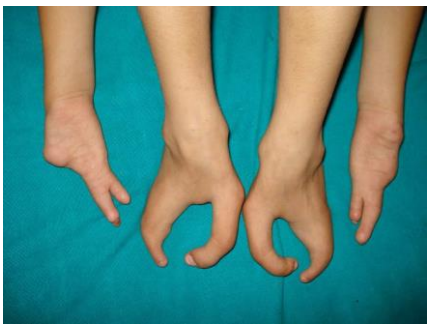
Dose-Response Curves

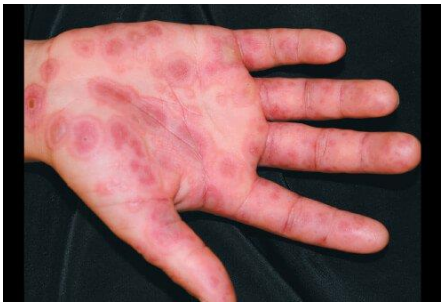
Dose-Response curves represent the relationship between the dose of radiation a person receives and the cellular response to that exposure.

- **Linear:** the response is directly related to the dose. As the dose increases, the response increases proportionately.
- **Non-linear:** the response is not proportionate to the dose. An increase in dose may result in a larger or smaller increase in the response depending on the location on the dose-response curve.
- **Threshold:** this represents the dose at which effects are produced; below this dose, there are no obvious effects.
- **Non-threshold:** any dose, no matter how small, will produce a response.



- **Stochastic effect:** occurs by chance, usually without a threshold level of dose. The probability of a stochastic effect is increased with increasing doses, but the severity of the response is not proportional to the dose (e.g., two people may get the same dose of radiation, but the response will not be the same in both people). Genetic mutations and cancer are the two main stochastic effects.





- **Deterministic effect:** health effects that increase in severity with increasing dose above a threshold level. Usually associated with a relatively high dose delivered over a short period of time. Skin erythema (reddening) and cataract formation from radiation are two examples of deterministic effects.

Biological effects of radiation

The harmful effects caused to human beings and other living beings due to their exposure to radiation is called as biological effects of radiation.

Radiation Causes Ionizations of: ATOMS which may affect MOLECULES which may affect CELLS which may affect TISSUES which may affect ORGANS which may affect THE WHOLE BODY

Biological effects of radiation on living cells may result in three outcomes:

1- Cells are undamaged by the dose

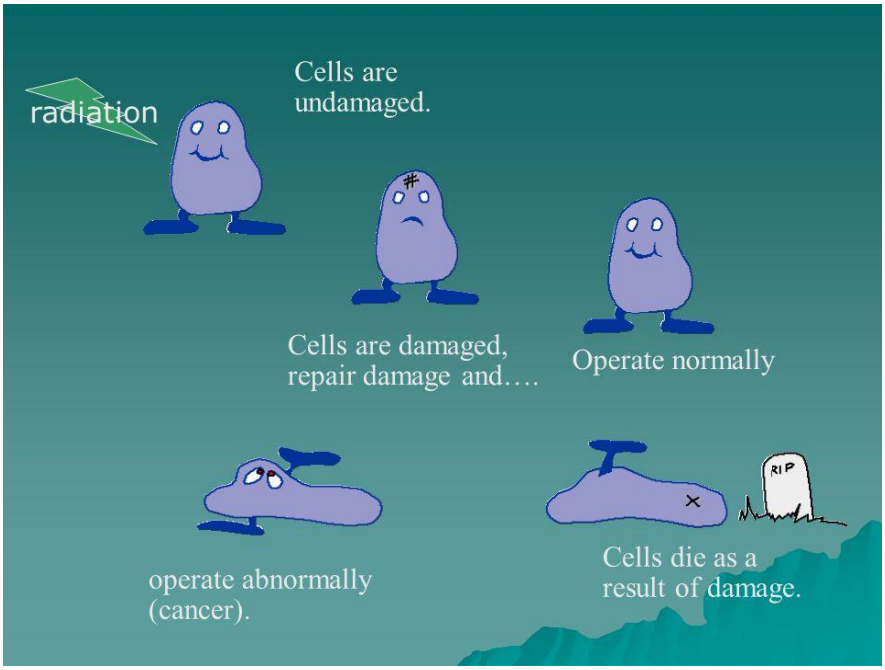
Ionization may form chemically active substances which in some cases alter the structure of the cells. These alterations may be the same as those changes that occur naturally in the cell and may have no negative effect.

2- Cells are damaged, repair the damage and operate normally

Some ionizing events produce substances not normally found in the cell. These can lead to a breakdown of the cell structure and its components. Cells can repair the damage if it is limited. Even damage to the chromosomes is usually repaired.

3- Cells die as a result of the damage

If a cell is extensively damaged by radiation or damaged in such a way that reproduction is affected, the cell may die. Radiation damage to cells may depend on how sensitive the cells are to radiation.



Radiosensitive Cells

Cells that are more easily damaged by radiation are radiosensitive.

The characteristics of radiosensitive cells are:

1. High reproductive rate (many mitoses)
2. Undifferentiated (immature)
3. High metabolic rate

Lymphocytes, germ cells, basal cells of skin and mucosa, and erythroblasts are examples of radiosensitive cells.

Radioresistant Cells

Cells that are not as susceptible to damage from radiation are radioresistant.

The characteristics of radioresistant cells are:

1. Low reproductive rate (few mitoses)
2. Well differentiated (mature)
3. Low metabolic rate

Nerve and muscle cells are examples of radioresistant cells.

Cellular Damage mechanisms

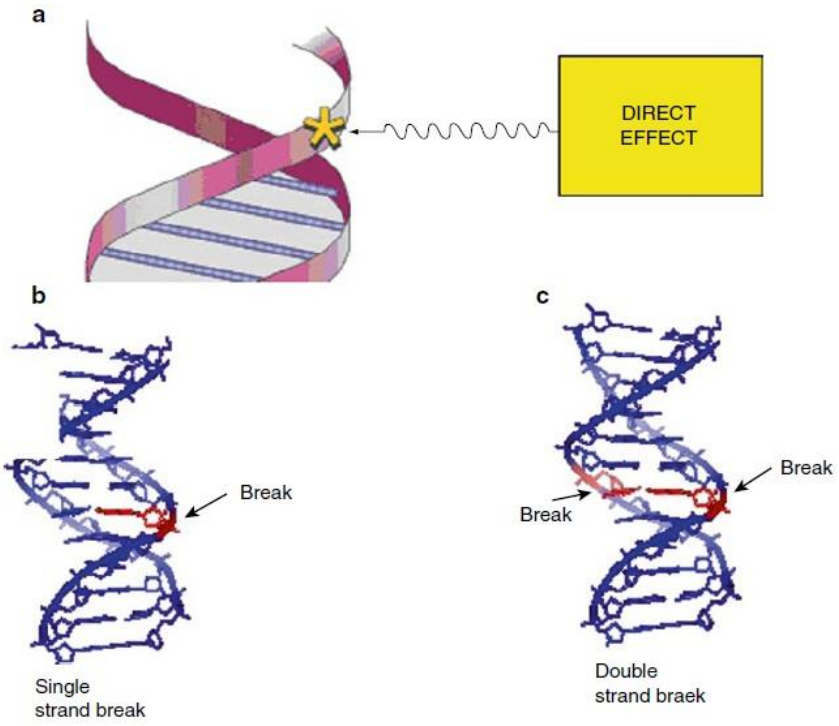
Even though all subsequent biological effects can be traced back to the interaction of radiation with atoms, there are two mechanisms by which radiate on ultimately affects cells.

These two mechanisms are commonly called direct and indirect effects.

Direct Effect

If radiation interacts with the atoms of the DNA molecule, or some other cellular component critical to the survival of the cell, it is referred to as a direct effect.

Such an interaction may affect the ability of the cell to reproduce and, thus, survive. If enough atoms are affected such that the chromosomes do not replicate properly, or if there is significant alteration in the information carried by the DNA molecule, then the cell may be destroyed by "direct" interference with its life sustaining system.

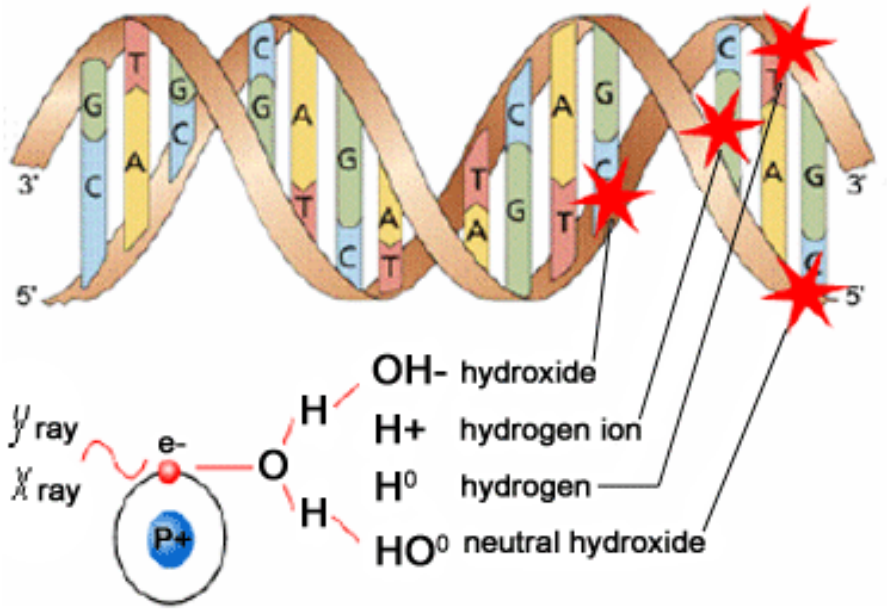


Indirect Effect

If a cell is exposed to radiation, the probability of the radiation interacting with the DNA molecule is very small since these critical components make up such a small part of the cell. However, each cell, just as is the case for the human body, is mostly water.

Therefore, there is a <u>much higher probability of radiation interacting with the water that makes up most of the cell's volume.</u>

When radiation interacts with water, it may break the bonds that hold the water molecule together, producing fragments such as hydrogen (H) and hydroxyls (OH). These fragments may recombine or may interact with other fragments or ions to form compounds, such as water, which would not harm the cell. However, they could combine to form toxic substances, such as hydrogen peroxide (H_2O_2), which can contribute to the destruction of the cell.



Radiation Effect Modifiers

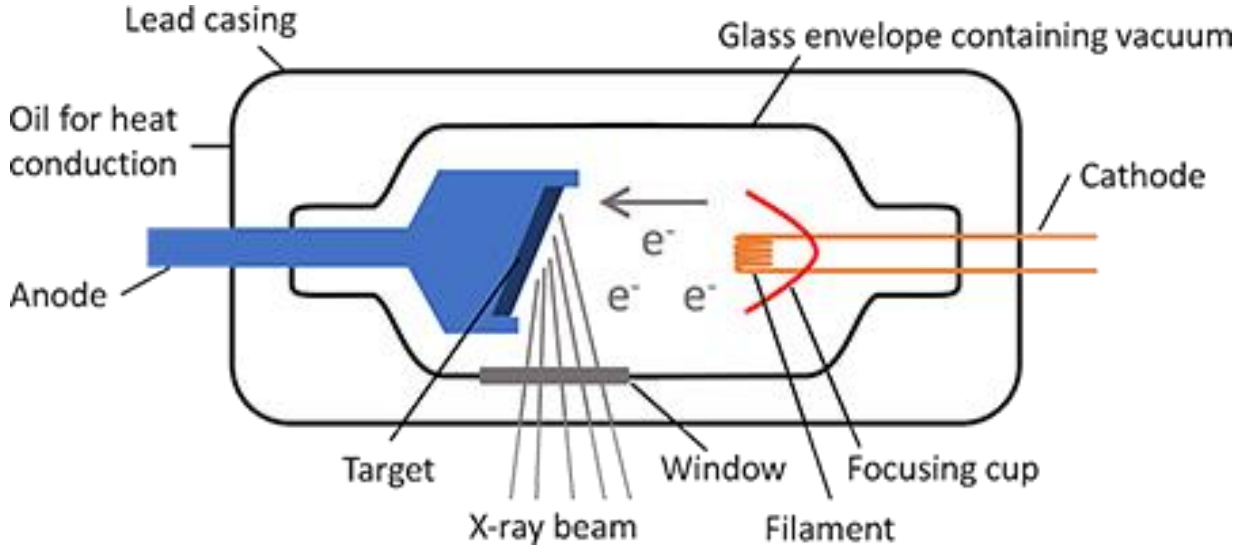
The biological response to radiation is dependent on several different factors. These include:

- **Total Dose:** the higher the radiation dose, the greater the potential cellular damage.
- **Dose Rate:** A high dose given over a short period of time (or all at once) will produce more damage than the same dose received over a longer period of time.
- **Total Area Covered:** the more cells that are exposed to radiation, the greater the effects will be.

- **Type of tissue:** As discussed earlier, radiosensitive cells are more likely to be damaged by radiation than are radioresistant cells.
- **Age:** Because the cells are dividing more frequently in a growing child, young people are affected more by radiation than are older people.
- **Linear Energy Transfer:** This measures the rate of the loss of energy as radiation moves through tissue. Particulate radiation (alpha particles, electrons, etc.) has a higher LET because it has mass and interacts with tissues much more readily than do x-rays.
- **Oxygen Effect:** Radiation effects are more pronounced in the presence of oxygen. Oxygen is required for the formation of the hydroperoxyl free radical, which is the most damaging free radical formed following ionization.

X- ray imaging

An X-ray tube is a vacuum tube that converts electrical input power into X-rays. X-ray tubes evolved from experimental Crookes tubes with which X-rays were first discovered on November 8, 1895, by the German physicist Wilhelm Conrad Röntgen. The availability of this controllable source of X-rays created the field of radiography, the imaging of partly opaque objects with penetrating radiation. In contrast to other sources of ionizing radiation, X-rays are only produced as long as the X-ray tube is energized. X-ray tubes are also used in CT scanners, airport luggage scanners, X-ray crystallography, material and structure analysis, and for industrial inspection.



- ✓ X-rays are generated in an x-ray tube. The tube consists of a cathode (negative electrical charge) and an anode (positive electrical charge).
- ✓ An x-ray beam is generated by passing an electron beam through a vacuum between a cathode (-) and an anode (+). The positively charged anode attracts the rapidly moving, negatively charged electrons.
- ✓ In the x-ray tube, a stream of fast-moving electrons is attracted and directed from the cathode to the anode. As the electrons collide and interact with the atoms on the anode target, a great amount of energy is produced. 1% of this energy is in the form of x-radiation. 99% appears as heat and must be removed from the anode.
- ✓ The tube enclosure is shielded, and a series of lead shutters allow the diagnostic beam to exit.
- ✓ The cathode consists of a wire filament that emits electrons when heated. The temperature of the filament is controlled by the milliamperage (mA) setting on the control panel of the machine.
- ✓ As the mA is increased, the temperature of the filament is increased, and the filament produces more electrons. The period of time during which the x-rays are permitted to leave the x-ray tube is measured in fractions of a second. The number of electrons available and the time period set for their release from the filament determines how many x-rays are produced from the anode. The mAs thus controls the total number of x-rays produced.
- ✓ The anode, which attracts the negatively charged electrons, is constructed at an angle so that the x-rays produced are directed downward (toward the film) through a window in the metal housing of this x-ray tube. In some machines the anode spins on a rotor.

Properties of X- ray

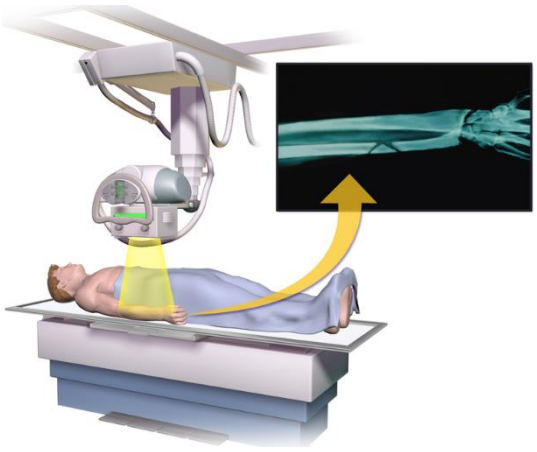
- ✓ X-ray photons carry enough energy to ionize atoms and disrupt molecular bonds. This makes it a type of ionizing radiation, and therefore harmful to living tissue. A very high radiation dose over a short period of time causes radiation sickness, while

lower doses can give an increased risk of radiation-induced cancer. In medical imaging this increased cancer risk is generally greatly outweighed by the benefits of the examination. The ionizing capability of X-rays can be utilized in cancer treatment to kill malignant cells using radiation therapy. It is also used for material characterization using X-ray spectroscopy.

- ✓ Hard X-rays can traverse relatively thick objects without being much absorbed or scattered. For this reason, X-rays are widely used to image the inside of visually opaque objects. The most often seen applications are in medical radiography and airport security scanners, but similar techniques are also important in industry (e.g. industrial radiography and industrial CT scanning) and research (e.g. small animal CT). The penetration depth varies with several orders of magnitude over the X-ray spectrum. This allows the photon energy to be adjusted for the application so as to give sufficient transmission through the object and at the same time provide good contrast in the image.
- ✓ X-rays have much shorter wavelengths than visible light, which makes it possible to probe structures much smaller than can be seen using a normal microscope. This property is used in X-ray microscopy to acquire high resolution images, and also in X-ray crystallography to determine the positions of atoms in crystals.

Medical uses

1- Projectional radiographs



- **Projectional radiography** is the practice of producing two-dimensional images using x-ray radiation. Bones contain much calcium, which due to its relatively high atomic number absorbs x-rays efficiently. This reduces the number of X-rays reaching the detector in the shadow of the bones, making them clearly visible on the radiograph. The lungs and trapped gas also show up

clearly because of lower absorption compared to tissue, while differences between tissue types are harder to see.

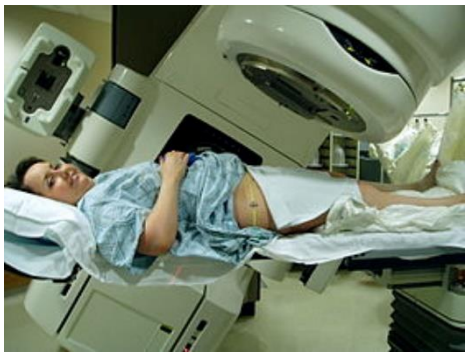
- **Projectional radiographs** are useful in the detection of pathology of the skeletal system as well as for detecting some disease processes in soft tissue. Some notable examples are the very common chest X-ray, which can be used to identify lung diseases such as pneumonia, lung cancer, or pulmonary edema, and the abdominal x-ray, which can detect bowel (or intestinal) obstruction, free air (from visceral perforations) and free fluid (in ascites). X-rays may also be used to detect pathology such as gallstones (which are rarely radiopaque) or kidney stones which are often (but not always) visible.
- **Traditional plain X-rays** are less useful in the imaging of soft tissues such as the brain or muscle. One area where projectional radiographs are used extensively is in evaluating how an orthopedic implant, such as a knee, hip or shoulder replacement, is situated in the body with respect to the surrounding bone.
- **Dental radiography** is commonly used in the diagnoses of common oral problems, such as cavities.
- **To generate an image of the cardiovascular system,** including the arteries and veins (angiography) an initial image is taken of the anatomical region of interest. A second image is then taken of the same region after an iodinated contrast agent has been injected into the blood vessels within this area. These two images are then digitally subtracted, leaving an image of only the iodinated contrast outlining the blood vessels. The radiologist or surgeon then compares the image obtained to normal anatomical images to determine whether there is any damage or blockage of the vessel.

2- Fluoroscopy

Fluoroscopy is an imaging technique commonly used by physicians or radiation therapists to obtain real-time moving images of the internal structures of a patient

through the use of a fluoroscope. In its simplest form, a fluoroscope consists of an X-ray source and a fluorescent screen, between which a patient is placed. However, modern fluoroscopes couple the screen to an X-ray image intensifier and CCD video camera allowing the images to be recorded and played on a monitor. This method may use a contrast material. Examples include cardiac catheterization (to examine for coronary artery blockages) and barium swallow (to examine for esophageal disorders).

3- Radiotherapy



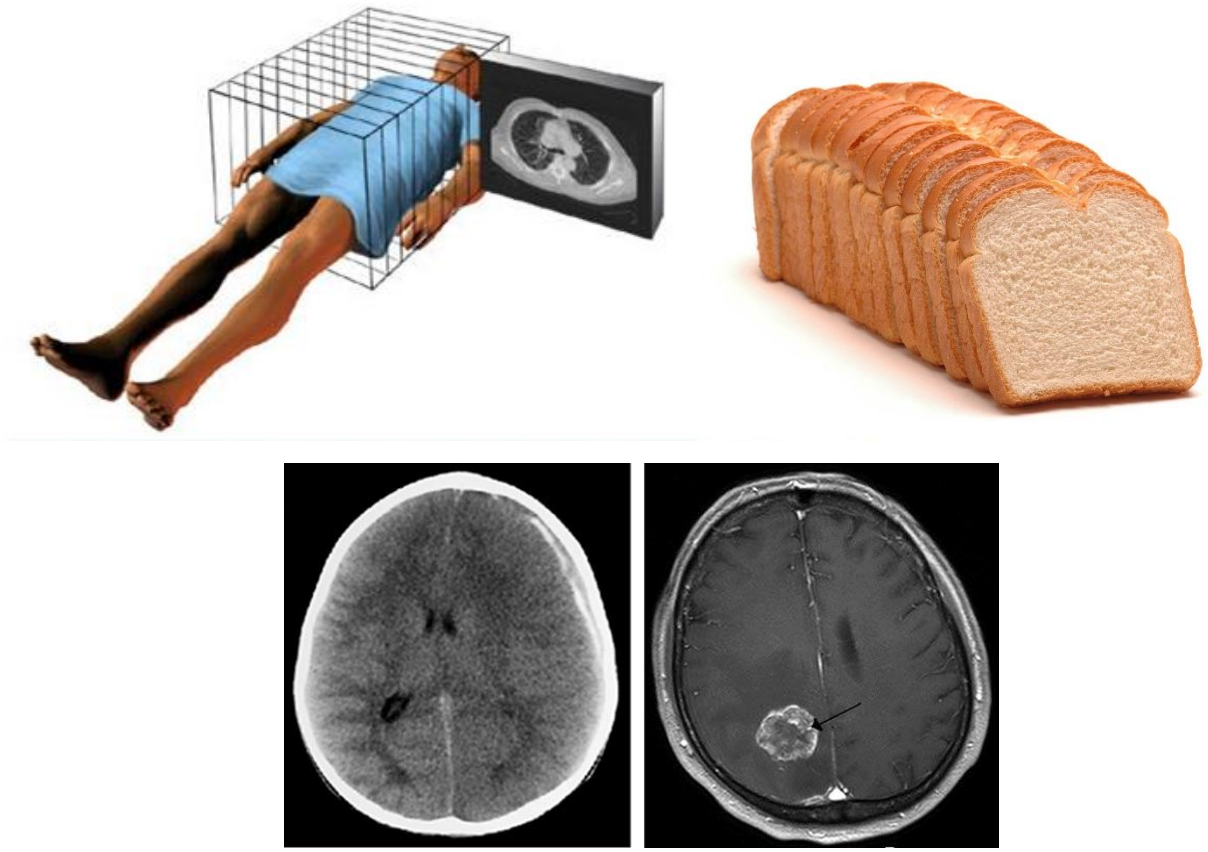
The use of X-rays as a treatment is known as radiation therapy and is largely used for the management (including palliation) of cancer; it requires higher radiation doses than those received for imaging alone. X-rays beams are used for treating skin cancers using lower energy x-ray beams while higher energy beams are used for treating cancers within the body such as brain, lung, prostate, and breast.

Computed Tomography (CT)

The ability of each tissue of the human body to X-rays is different than other tissues. Quantitatively, the absorption of X-rays varies from tissue to tissue. These characteristic properties of tissues can be exploited for some useful applications. Computed tomography or CT is one of those important applications that work on the principle of X-ray absorption by body tissues. CT (CAT) scanning is a noninvasive medical test that helps physicians to diagnose and treat medical conditions. This technique uses special X-ray equipment and high-quality computers to produce multiple images of the inside of a desired part of the body. The images taken are 3-D usually. Those images are then examined on a computer, and appropriate treatments are prescribed by the physicians accordingly.

A CT image is usually called a slice, as it corresponds to what the object being scanned would look like if it were sliced open along a plane. An even better analogy is a slice from a loaf of bread, because just as a slice of bread has a thickness, a CT slice corresponds to a certain thickness of the object being scanned. So, while a typical

digital image is composed of pixels (picture elements), a CT slice image is composed of voxels (volume elements). Taking the analogy one step further, just as a loaf of bread can be reconstituted by stacking all of its slices, a complete volumetric representation of an object is obtained by acquiring a contiguous set of CT slices.

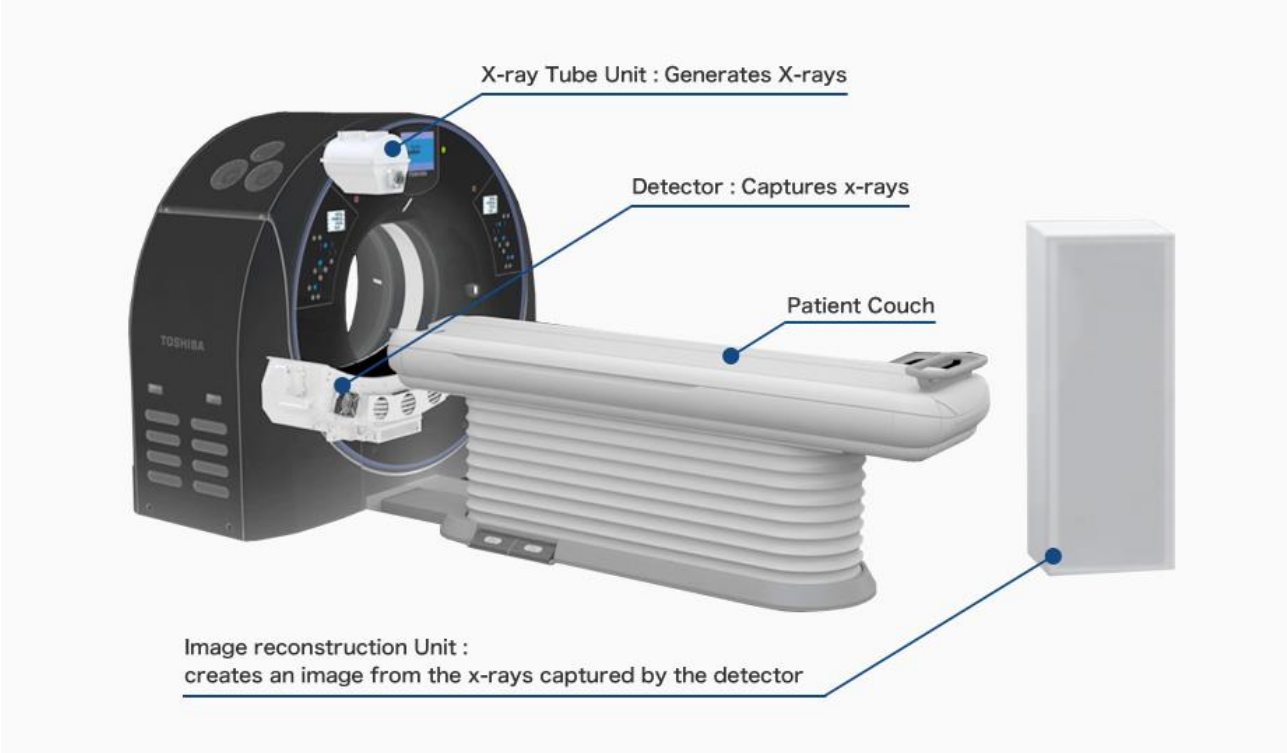


CT image of normal human brain (left) and human brain containing a tumor (right).

Computed Tomography Components

a) **Framework** with a central opening, into which the patient is moved during the examination.

b) **X-ray tube,** the source of the X-rays that pass through the body situated in the gantry in the form of a series of projections.



c) **Detector array,** converts the projection values, in the form of radiation intensities, into electrical quantities. Usually, the whole detector array rotates synchronously with the X-ray tube around the test object.

d) **Table** allows the patient to be maneuvered easily into position.

CT Scanner Design

One of three basic tube-detector projection systems:

- **A projection system using a parallel beam of radiation (Parallel-beam system)**
- **A system using a beam of radiation in the shape of a fan (Fan-beam system)**
- **A system using a beam of radiation in the shape of a cone (Cone-beam system)**

Basic Principles

1. **In CT scan, multiple pencil or fan beams of kilovoltage (kV) X-rays (photons) pass through a desired volume of body from multiple angles (usually over 180 degrees).**
2. **A dosimeter is placed on the opposite side of the volume which measures the amount of X-rays reaching it. This allows determination of the attenuation of individual beams as they pass through the volume.**

3. It must be noted that when high energy X-rays pass through a tissue or a material, attenuation (absorption scattering) of the beam occurs. However, at low energies (kV) scattering is negligible; therefore, only absorption of X-rays is considered in CT where kV beam is used.

4. Each part of the volume may be considered a "voxel" (a three-dimensional pixel) with width, height, and depth. Each beam will pass through a number of voxels as it traverses the volume.

5. The absorption of the beam as it passes through the volume may be considered to be the sum of absorptions in each voxel it has passed through. This may be up to 512 voxels for modern scanners. The passage of X-ray beams from different directions, passing and absorbed by a slice of the body and detected by detectors.

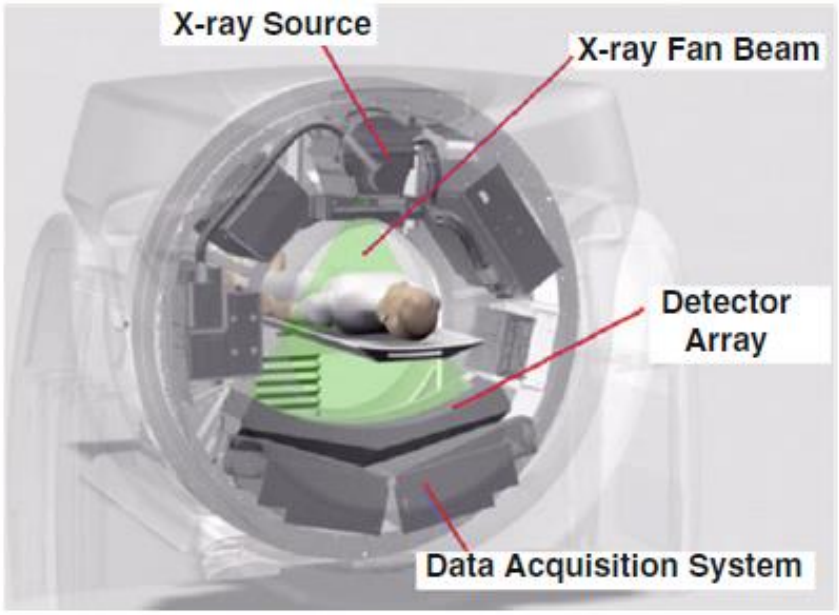
6. A computer is then used to solve a simultaneous equation with up to 512 variables, using the absorption information from each beam in the form of absorption coefficients "μ." This is a process which computers are able to perform quickly and precisely, so long as they have been given good information from the photon absorption. Once the absorption for each voxel is determined, the computer system assigns a Hounsfield unit to each part of the volume.

7. Hounsfield units (special units in CT) range from -1000 (air) to 0 (water) and to +1000 (cortical bone). Table 8.1 shows the absorption coefficients (μ) of various parts of the body as compared to the absorption coefficients of air and water.

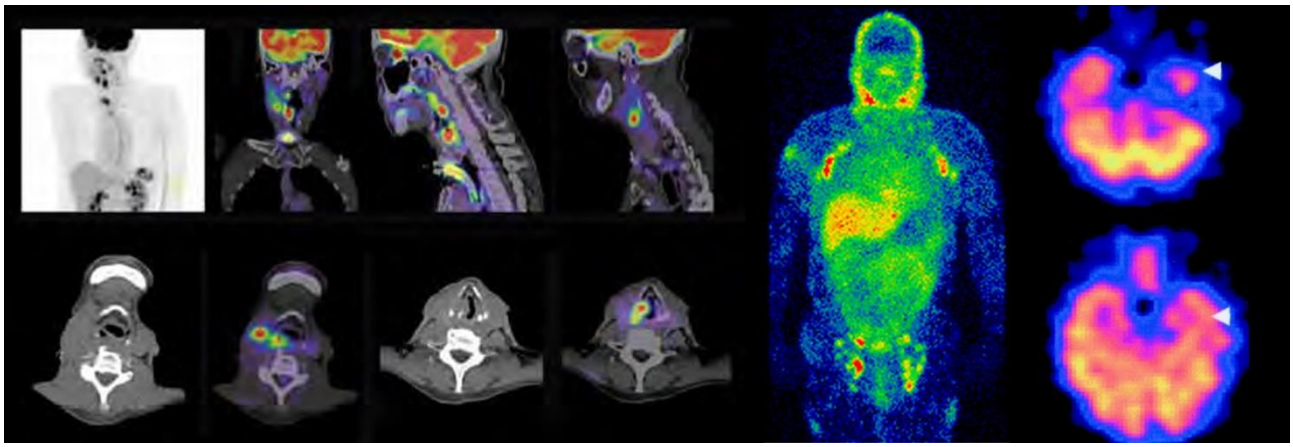
Tissue	Absorption coefficient μ (cm^{-1})
Air	0.0004
Fat	0.185
Water	0.206
Blood	0.208

Gray matter	**0.212**
White matter	**0.213**
Bone	**0.528**

The use of kilovoltage photons allows a good discrimination between tissues of different atomic numbers. Because so many beams are used, CT is able to discriminate between different soft tissues (such as adipose and muscular tissue) even though they have similar atomic numbers. Another important feature is the kilovoltage photons are only affected by the intervening tissue, and spatial resolution (the accuracy of determining the physical position of each voxel) is very high and allows accurate planning.



Physics of Nuclear Medicine



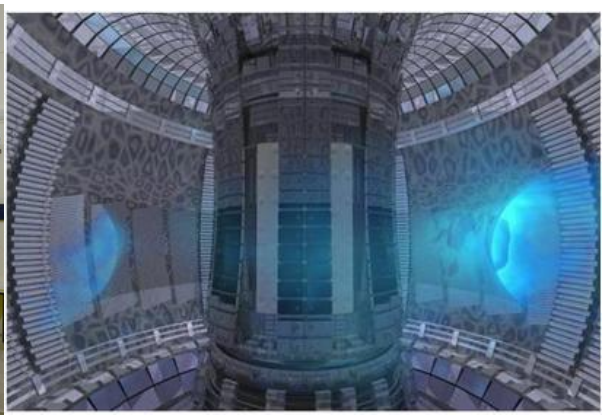
Nuclear Medicine

Nuclear medicine is a branch of physics that utilizes nuclear technology for the diagnosis and treatment of diseases. It covers radionuclide production, interaction, detection, and imaging. It also involves radiation dosimetry and radionuclide therapy procedures.

Various radiations are used in nuclear medicine. Those radiations are usually obtained from radiation-emitting materials called radioisotopes or radiopharmaceuticals. Radioisotopes could be a naturally existing radioactive material like $_{92}U^{238}$, or a stable atom of a material can be converted to a radioisotope by destabilizing it.

Common Radioisotopes

Radioisotopes are produced by two methods. One method is called accelerator-based production method and the other method is known as nuclear reactor-based



Radiotracers

Suitable radionuclides are selected based on

- **high enough photon energy to exit body, but low enough to be detected: Typically, 100 to 500 keV**
- **half-life of a few hours**
- **'clean' photon-emission decay, i.e. no alpha and beta particles, which add radiation dose**
- **The radiotracer (ligand + radionuclide) must have suitable biodistribution, clearance, and be safe in 'trace' amounts**

• Example

^{99m}Tc-labelled for myocardial (cardiac muscle) and blood perfusion imaging

Half-Life

The time taken by a radioisotope to reduce to half of its initial number of atoms is called its half-life $T_{1/2}$. A mathematical expression for half-life is obtained by replacing $N = N_0/2$ and $t = T_{1/2}$. Making these substitutions, we get

$$T_{1/2} = 0.693/\lambda$$

This natural half-life of a radioisotope is also called its physical half-life.

Mean- Life

When a radioactive element decays, the first atom takes almost no time to decay. On the other hand, some atoms may take hours, days, and years to decay. Therefore, the idea of mean life describes the average time for which an atom survives before it decays. Mathematically, the mean life T is defined as

$$\mathbf{T = 1/\lambda}$$

Physical half-life $T^p_{1/2}$

The natural half-life of a radioactive isotope (discussed already).

Biological half-life $T^b_{1/2}$

The time in which half of the radioisotope is excreted by the body through metabolic activities. Bodies' metabolic activities affect different foods and materials in a different way. Some materials can be excreted by the body with a slower rate and others can be excreted faster.

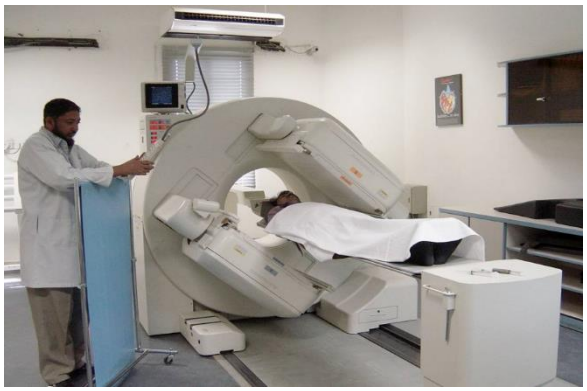
Effective half-life $T^{e}_{1/2}$

The time in which a radioisotope reduces to half when both methods of decay (natural decay and biological excretion) act at the same time. Mathematically:

$$1/T^{e}_{1/2} = 1/T^{p}_{1/2} + 1/T^{b}_{1/2}$$

Gamma Camera

The basics of using gamma rays to image is nuclear medical technique called a gamma camera. The gamma camera consists of four basic parts



1. **Collimators**
2. **Scintillation detector**
3. **Photomultiplier tube (PMT)**
4. **Electronics & computer elements**

Collimators

For gamma rays, the image is formed by a component called a collimator. The collimators are usually made out of a thick sheet of a heavy material usually lead, that is perforated like a honeycomb by long thin channels.

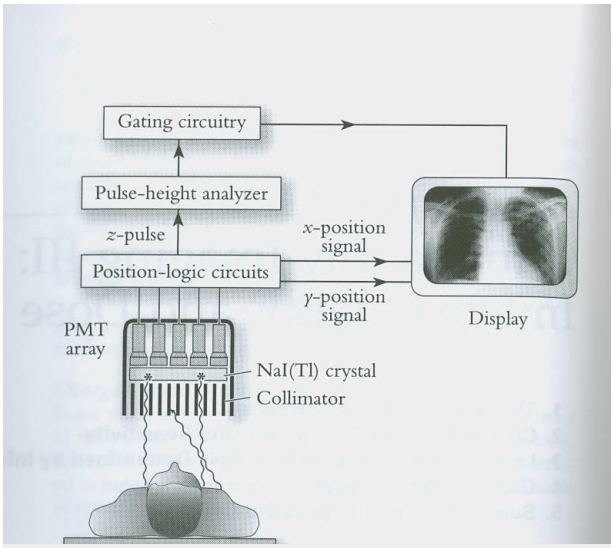
The collimator forms an image by selecting only the rays traveling in (or nearly in) a specific direction, in which the channels are oriented. Gamma rays traveling in other directions are either blocked by the channel walls or miss the collimator entirely.

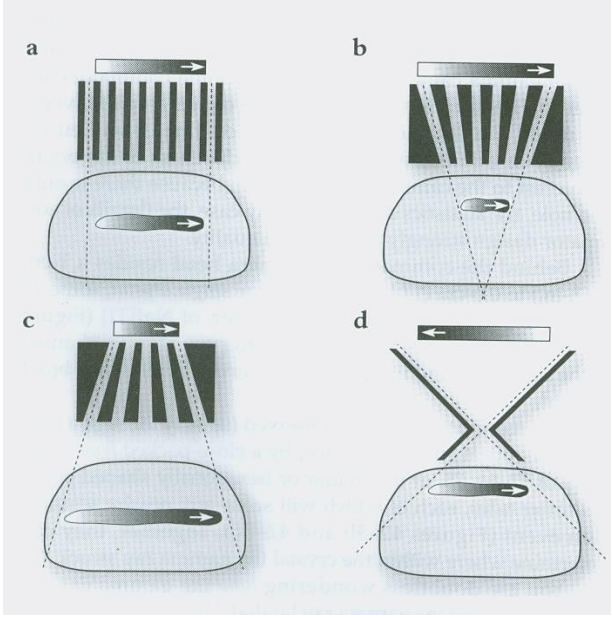
The collimator preferentially selects the direction of the incoming radiation.

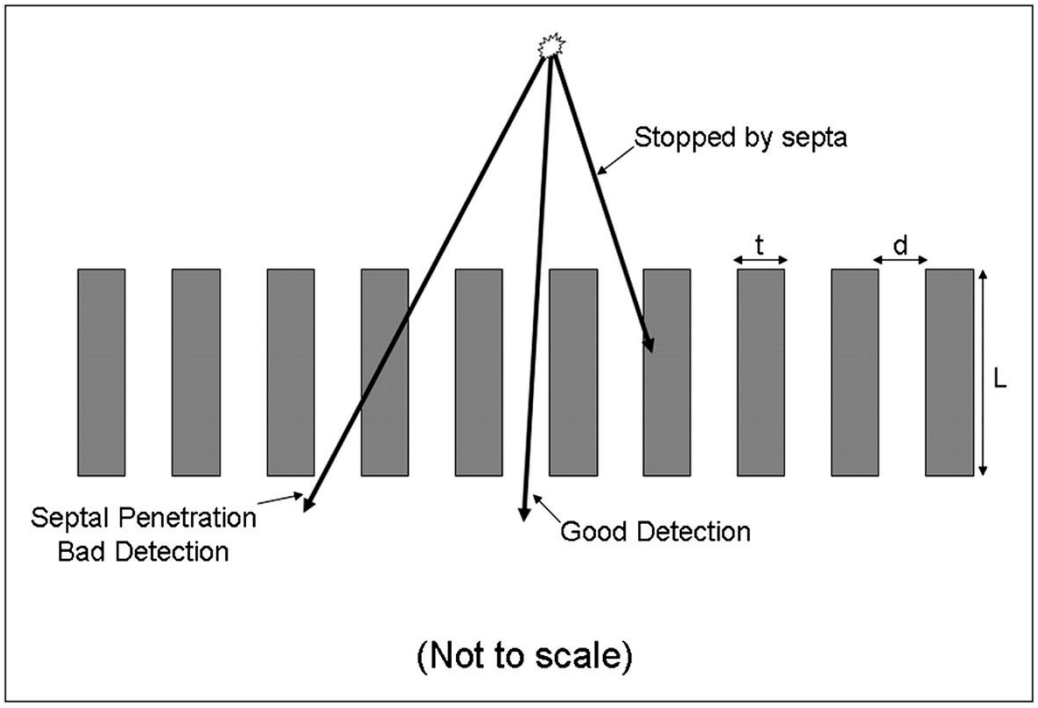
Gamma rays traveling at an oblique angle to the axes of the holes will strike the lead walls (septa) and not reach the crystal to be detected.

This allows only radiation traveling perpendicular to the crystal surface to pass and contribute to the resulting image.

A certain fraction (about 5%) of photons striking the septa will pass through them and reach the crystal; this phenomenon, which degrades image quality, is known as *septal penetration*.







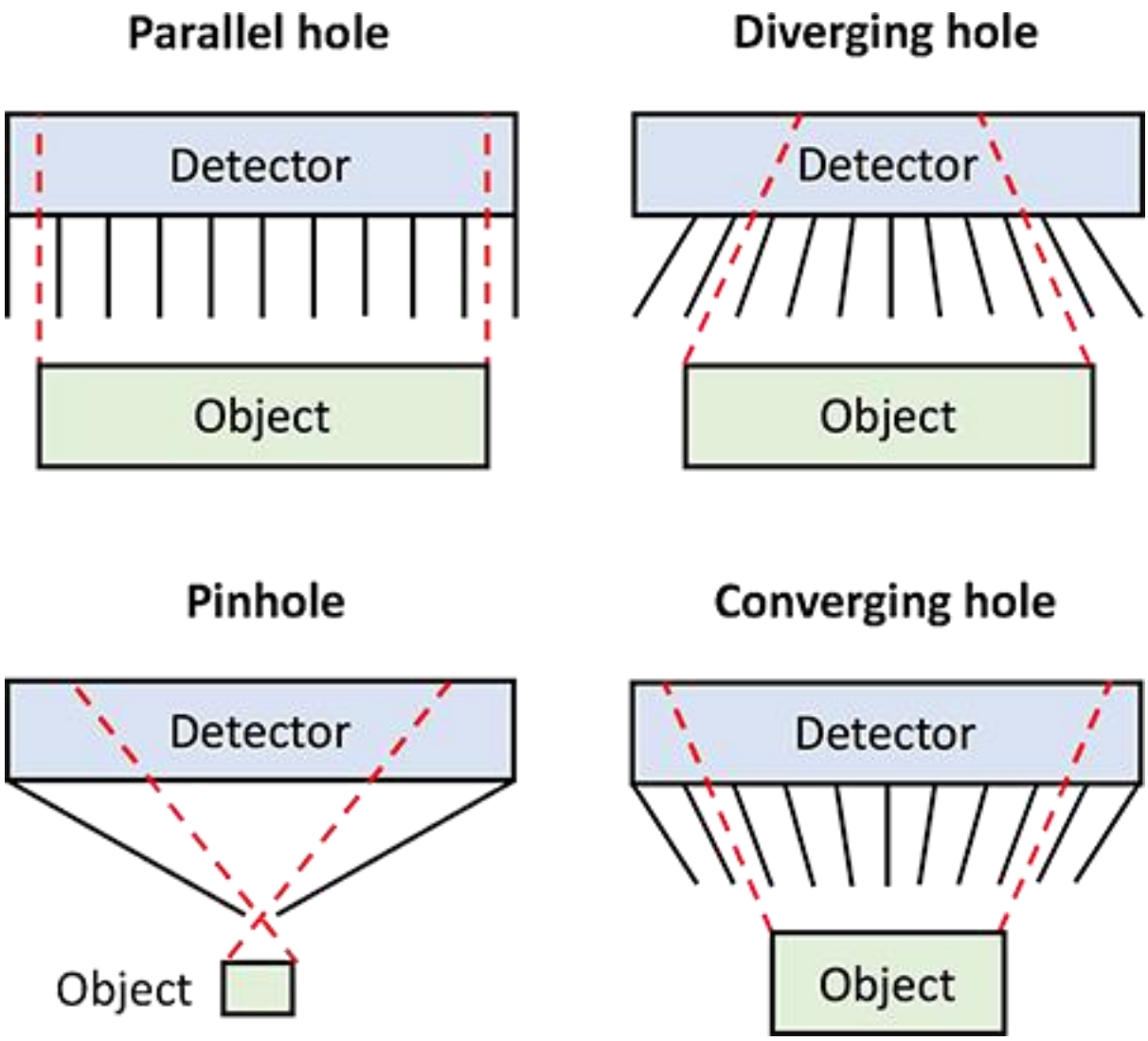
Collimator basic designs

1.Parallel hole: most common design

2.Converging

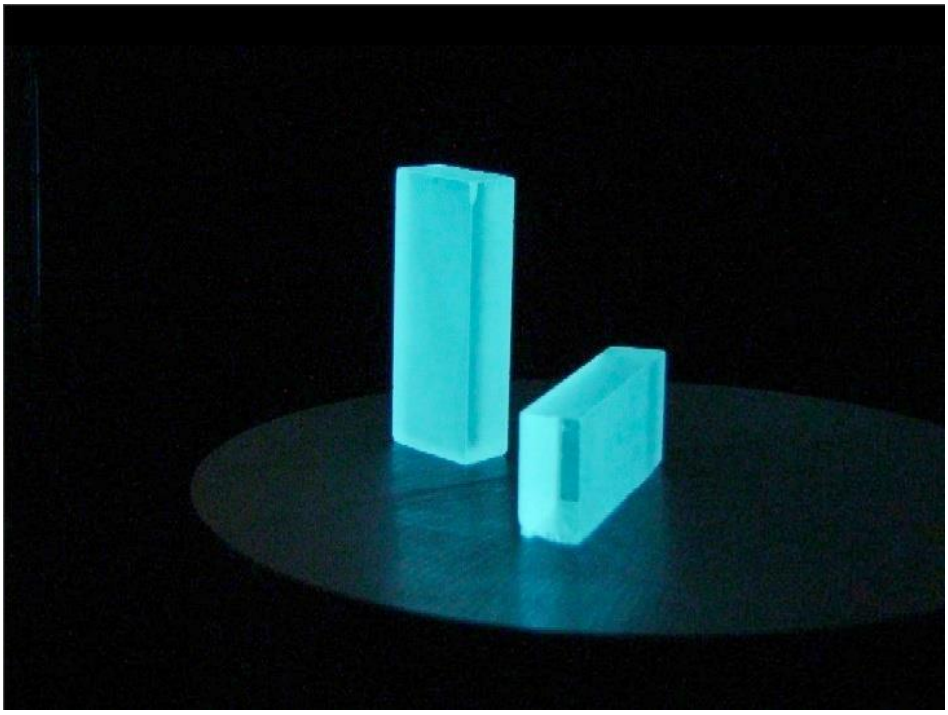
3.Diverging

4.Pinhole



Scintillation crystal (detector)

The detector crystal (NaI(TI)) is a single large area mostly made of sodium iodide (NaI) that are doped with small amounts of stable thallium (TI). The thallium atoms dispersed in the crystal improves its response to the gamma rays photons. NaI(TI) detector crystal, usually 6-12.5 mm thick, with sizes up to 60x40 cm.



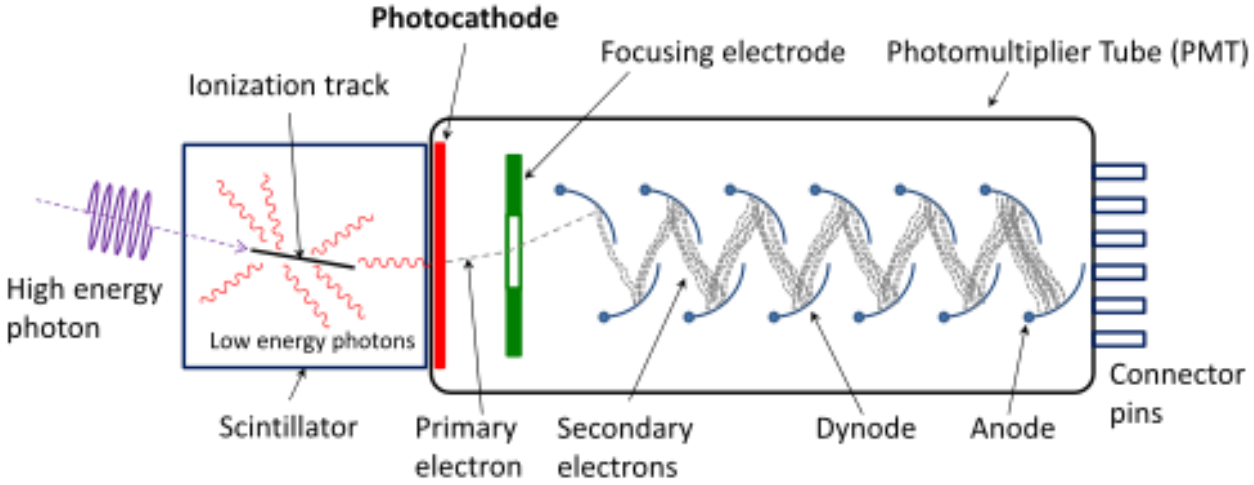
The process of converting gamma rays to light is complex. It can be summarized as the following:

- The gamma photon transfers its energy in one or more Compton or photoelectric interactions in the crystal
- Each of these energetic electrons produced by the gamma interactions in turn distributes its energy among electrons in the crystal leaving them in the excited state.
- As these return to their original state, some of their energy is released as light photons.
- For each KeV of gamma ray energy absorbed by the crystal, approximately 40 light photons are emitted
- PM tubes detect these light photons.

Photomultipliers tube

Photomultipliers are typically constructed with an evacuated glass housing containing a photocathode, several dynodes, and an anode. Incident photons strike the photocathode material, which is usually a thin vapor-deposited conducting layer on the inside of the entry window of the device. Electrons are ejected from the surface as a

consequence of the photoelectric effect. These electrons are directed by the focusing electrode toward the electron multiplier, where electrons are multiplied by the process of secondary emission.



Nuclear medicine scans

Nuclear medicine scans a very small amount (e.g., nanograms) of radioactive material called a radiotracer that is injected intravenously into the patient then accumulates in specific organs in the body

How much, how rapidly and where this uptake occurs are factors which can determine whether tissue is healthy or diseased

Three different modalities under the general umbrella of nuclear medicine

- **planar imaging**
- **Single photon emission computed tomography (SPECT)**
- **Positron emission tomography (PET)**

SPECT imaging

Single photon emission computed tomography (SPECT) is the method of obtaining cross-sectional nuclear images (similar to CT in x-ray imaging).

- **Single photon:** SPECT uses single gamma photon detection that are produced by gamma photon decay
- **Emission:** Radioactivity used to create image is emitted from patient rather than transmitted through patient from an outside source as is done in x-ray imaging

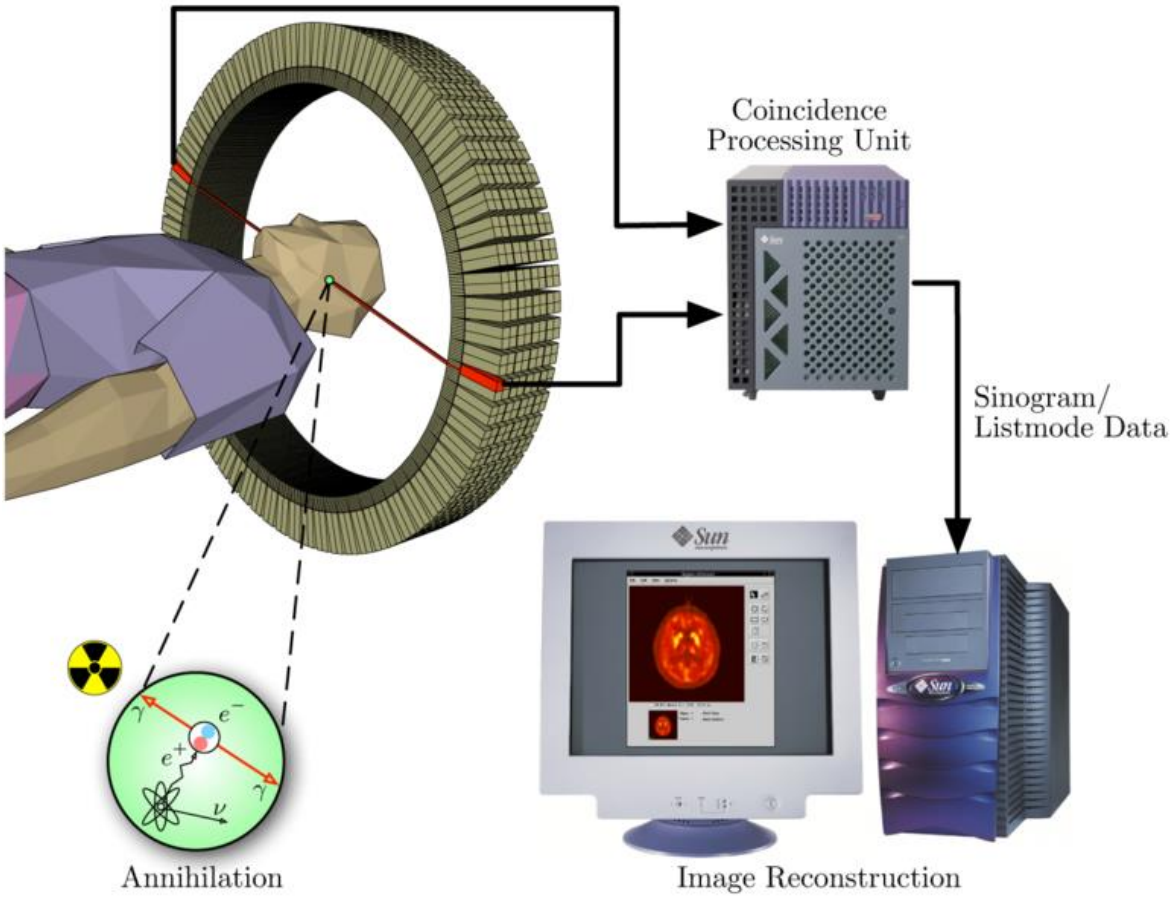
- **Computed tomography:** Slices are imaged that can be reconstructed into 3D data

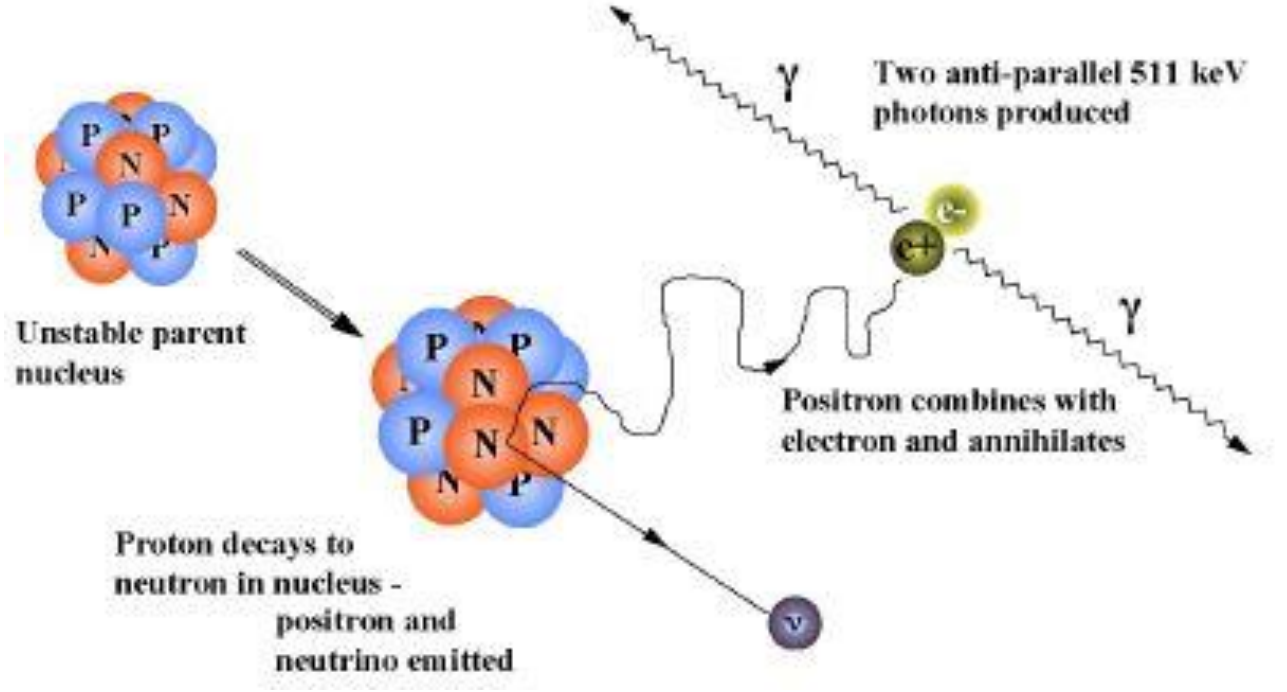
SPECT can be used to image any radiopharmaceutical in which:

The distribution does not change significantly during the image acquisition time (20-40 minutes). Acquisition time long enough for sufficient amount of gamma photons to be collected.

Positron emission tomography (PET)

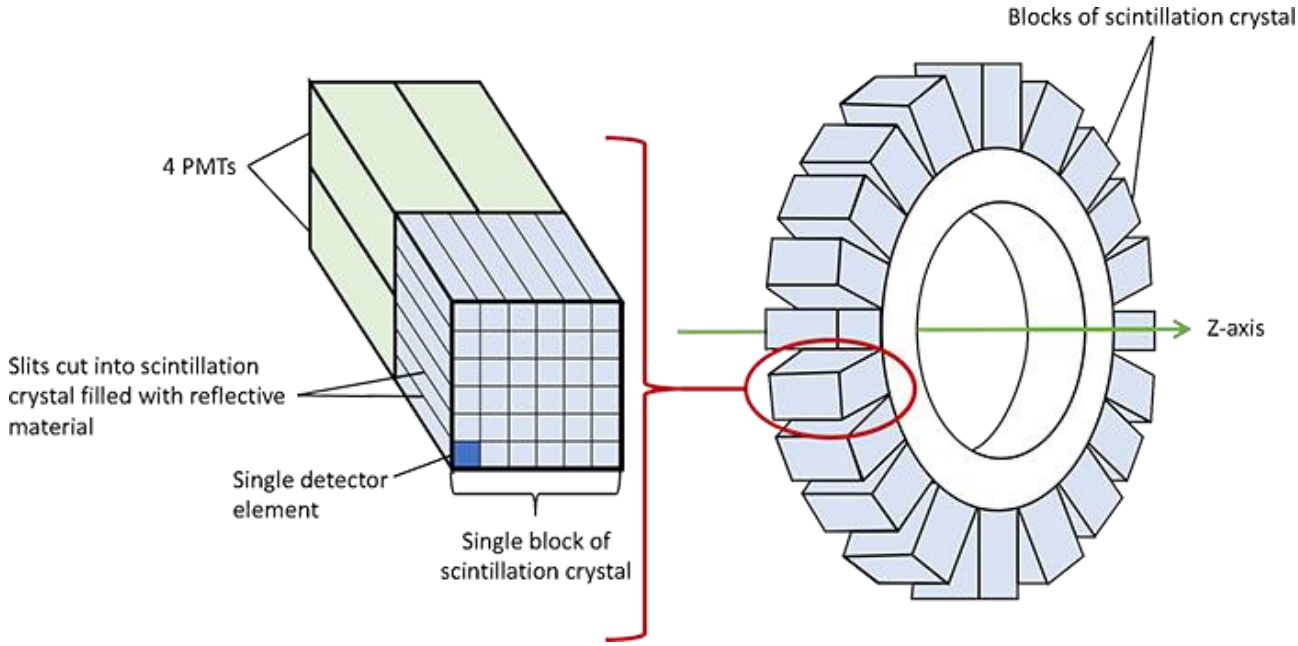
Similar to SPECT, PET is a form of tomographic nuclear imaging. However, PET relies on the near simultaneous detection of the pair of gamma photons that are released from an annihilation of a positron and an electron.





PET radiopharmaceuticals

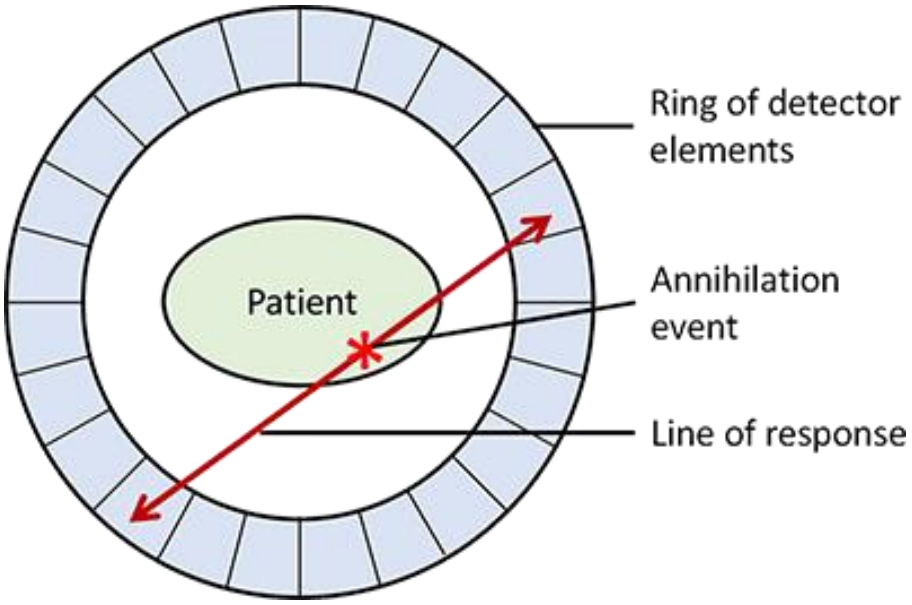
The most commonly used radionuclide is fluorine-18 and most common pharmaceutical label is fluorodeoxyglucose (FDG). FDG is a tracer for glucose metabolism.



Forming an image

The simultaneous gamma photon by opposite detector elements is called a coincidence and the line between the two detector elements is called the line of response. The detector elements also encode the total energy deposited by the gamma photons.

Coincident gamma photons (detected by two detectors along line of response within 1 nanosecond of each other) only are recorded and contribute to image



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