# Electricity within the body

## Electrical potentials of nerves

The ability of neurons to receive and transmit electrical signals is fairly well understood.

Across the surface or membrane of every neuron is an electrical potential (voltage) difference due to the presence of more negative ions on the inside of the membrane than on the outside. The neuron is said to be polarized. The inside of the cell is typically 60-90 mV more negative than the outside. This potential difference is called the resting potential of the neuron. Figure 1 shows schematically the typical concentrations of various ions inside and outside the membrane of an axon. When the neuron is stimulated a large momentary change in the resting potential occurs at the point of stimulation. This potential change, called the action potential, propagates along the axon. The action potential is the major method of transmission of signals within the body. The stimulation may be caused by various physical and chemical stimuli such as heat, cold, light, sound, and odors. If the stimulation is electrical, only about 20 mV across the membrane is needed to initiate the action potential.

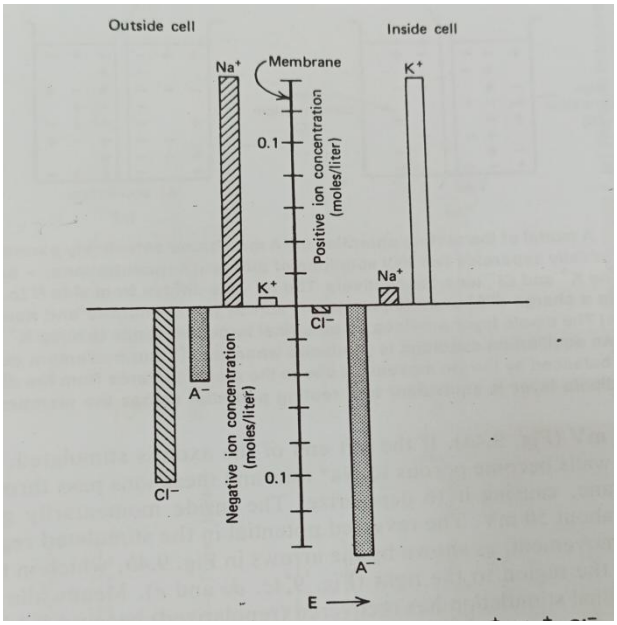



Figure 1

Examination of the axons of various neuron with an electron microscope indicates that there are two different types of nerve fibers. The membranes of some axons are covered with a fatty insulating layer called myelin that has small uninsulated gaps called nodes of Ranvier every few millimeters (Fig. 2); these nerves are referred to as myelinated nerves. The axons of other nerves have no myelin sleeve (sheath), and these nerves are called unmyelinated nerves.

Myelinated nerves, the most common type in humans, conduct action potential much faster than unmyelinated nerves.

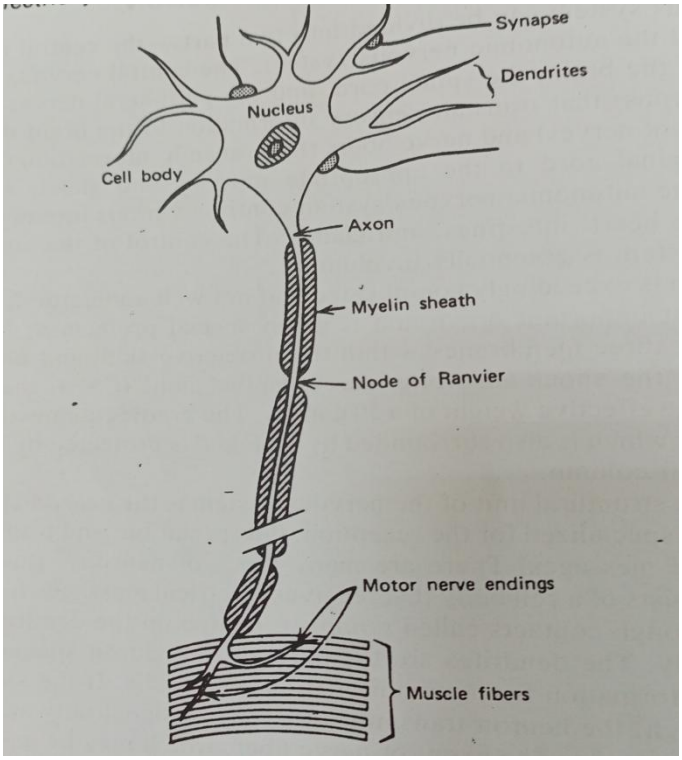



Figure 2

**Electromyogram (electrical signals from muscles)**

One means of obtaining diagnostic information about muscles is to measure their electrical activity. In this section we briefly trace the transmission of the action potential from the axon into the muscle, where it causes muscle contraction. The record of the potentials from muscles during movement is called the electromyogram, or EMG.

A muscle is made up of many motor units. A motor unit consists of a single branching neuron from the brain stem or spinal cord and the 25 to 2000 muscle fibers (cells) it connects to via motor end plates (Fig. 3a). The resting potential across the membrane of a muscle fiber is similar to the resting potential across a nerve fiber. Muscle action is initiated by an action potential that travels along an axon and is transmitted across the motor end plates into the muscle fibers, causing them to contract. The record of the action potential in a single muscle cell is shown schematically in Fig. 3b. Such a measurement is made with a very tiny electrode (microelectrode) thrust through the muscle membrane.

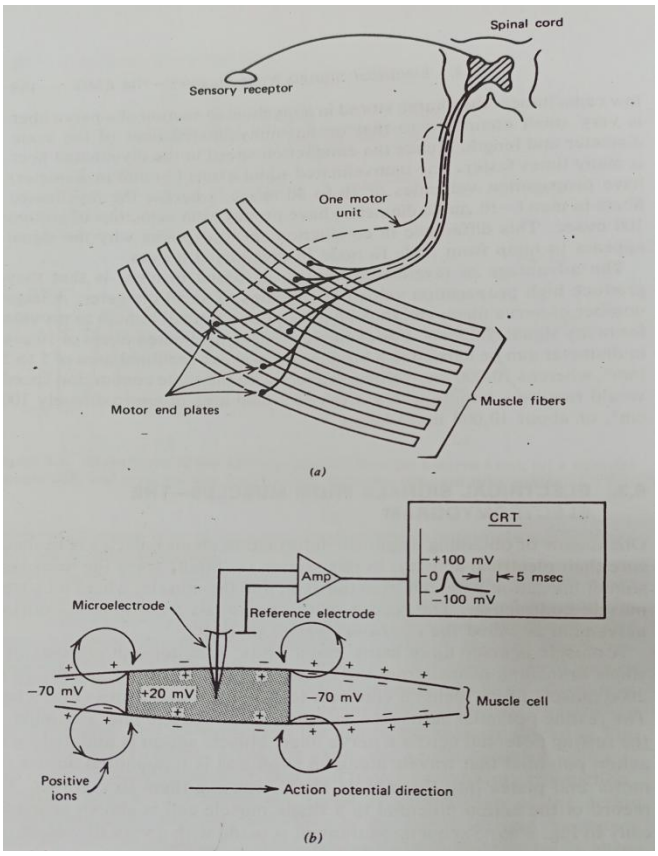



Figure 3

## The electrocardiogram (electrical signals from the heart)

The heart has a double pump and four chambers (Fig. 4); the two upper chambers, the left and right atria, are synchronized to contract simultaneously, as are the two lower chambers, the left and right ventricles. The right atrium receives venous blood from the body and pumps it to the right ventricle. This ventricle pumps the blood through the lungs, where it is oxygenated. The blood then flows into the left atrium. The contraction of the left atrium moves the blood to the left ventricle, which contracts and pumps it into the general circulation; the blood passes through the capillaries into the venous system and returns to the right atrium.

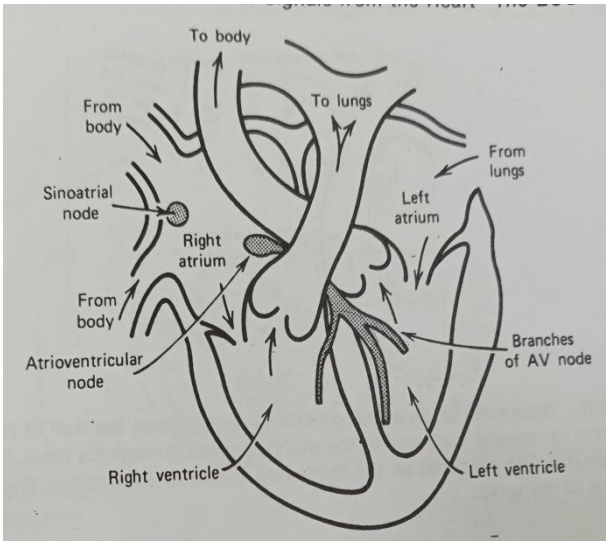



Figure 4

The rhythmical action of the heart is controlled by an electrical signal initiated by spontaneous stimulation of special muscle cells located in the right atrium. These cells make up the sinoatrial (SA) node, or the pacemaker (Fig. 4). The SA node fires at intervals about 72 times per minute; however, the rate of firing can be increased or decreased by nerves external to the heart that respond to the blood demands of the body as well as to other stimuli. The electrical signal from the SA node initiates the depolarization of the nerves and muscles of both atria, causing the atria to contract and pump blood into ventricles. Repolarization of the atria follows. The electrical signal then passes into the atrioventricular (AV) node, which initiates the depolarization of the right and left ventricles, causing them to contract and force blood into the pulmonary and general circulations. The ventricle nerves and muscles then repolarization and the sequence begins again.

The nerves and muscles of the heart can be regarded as sources of electricity enclosed in an electrical conductor, the torso. Obviously it is not practical to make direct electrical measurements on the heart; diagnostic information is obtained by measuring at various places on the surface of the body the electrical potentials generated by the heart. The record of the heart's potentials on the skin is called the electrocardiogram (ECG).

The relationship between the pumping action of the heart and the electrical potentials on the skin can be understood by considering the propagation of an action potential in the wall of the heart as shown in Fig. 5. The resulting current flow in the torso leads to a potential drops as shown schematically on the resistor. The potential distribution for the entire heart when the ventricles are one-half depolarized is shown by the equipotential lines in Fig. 6. Not

that the potential measured on the surface of the body depend upon the location if the electrodes.

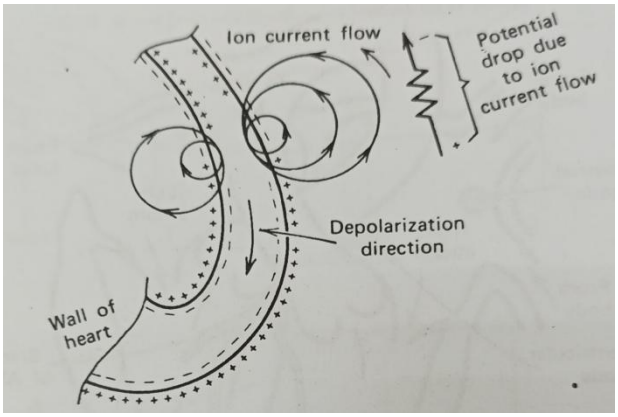



Figure 5

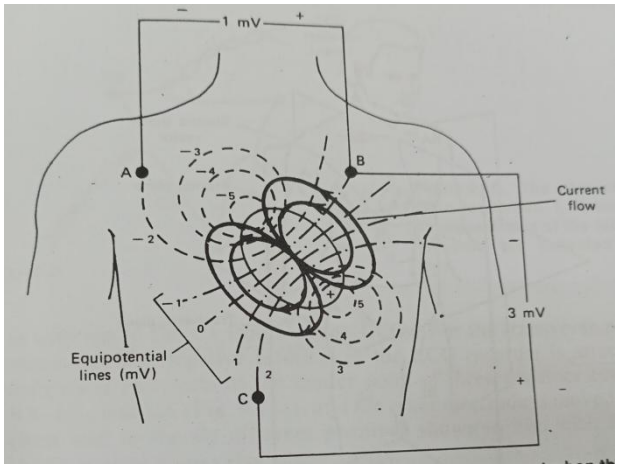



Figure 6

The electrical (cardiac) potential that we measure on the body's surface is merely the instantaneous projection of the electric dipole vector in a particular direction. As the vector changes with time, so does the projected potential. Figure 7 shows an electric dipole vector along with the three electrocardiographic body planes.

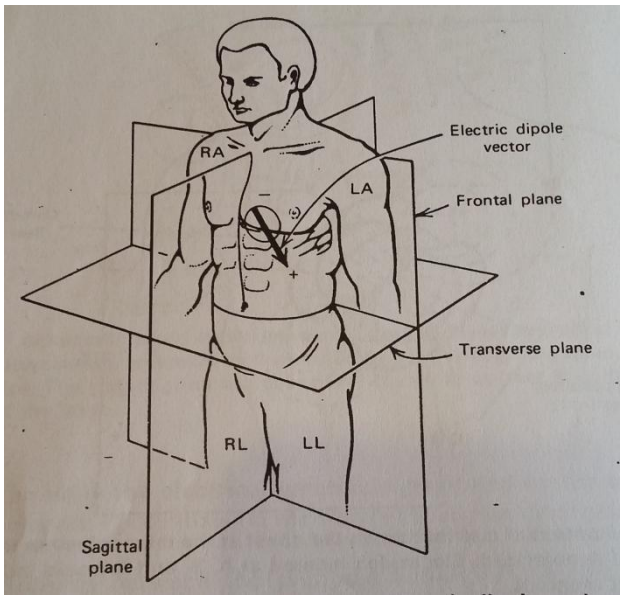



Figure 7

The surface electrodes for obtaining the ECG are most commonly located on the left arm (LA), right arm (RA), and left leg (LL), although the location of the electrodes can vary in different clinical situations; sometimes the hands or positions closer to the heart are used. The measurement of the potential between RA and LA is called Lead I, that between RA and LL is called Lead II, and that between LA and LL is called Lead III (Fig.8).

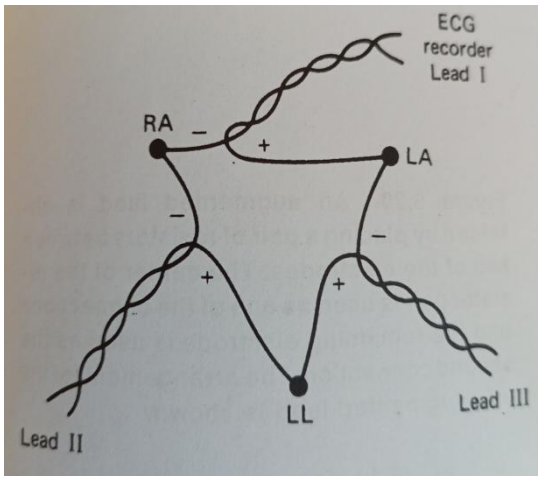



Figure 8

Three augmented lead configurations, $aV_R$ , $aV_L$ , and $aV_F$ , are also obtained in the frontal plane. For the $aV_R$ lead, one side of the recorder is connected to RA and the other side is connected to the center of two resistors connected to LL and LA (Fig. 9). The other two

augmented leads are obtained in a similar manner; for the $aV_L$ lead, the recorder is attached to the LA electrode and resistors are connected to RA and LL; for the $aV_F$ lead, the recorder is attached to the LL electrode and the resistors are connected to RA and LA.

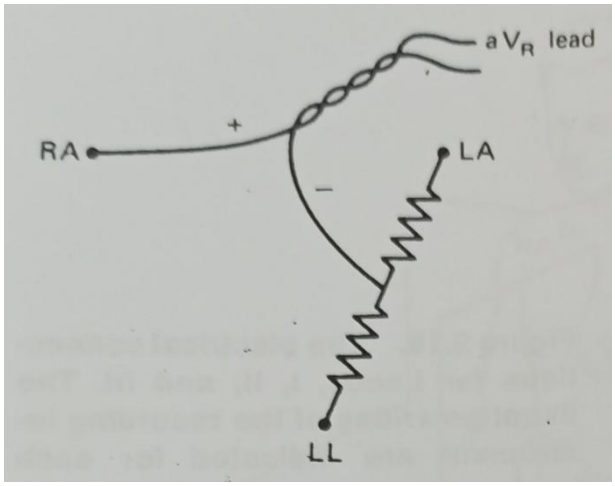



Figure 9

Each ECG tracing maps out a projection of the electric dipole vector, or the electrical activity of the heart, through each part of its cycle. Figure 10 shows schematically the Lead II output with the standard symbols for the parts of the pattern. The major electrical events of the normal heart cycle are:

1. The atrial depolarization, which produce the P wave**.**
2. The atrial repolarization, which is rarely seen and is unlabeled**.**
3. The ventricular depolarization which produces the QRS complex.
4. The ventricular repolarization, which produces the T wave (Fig. 10).

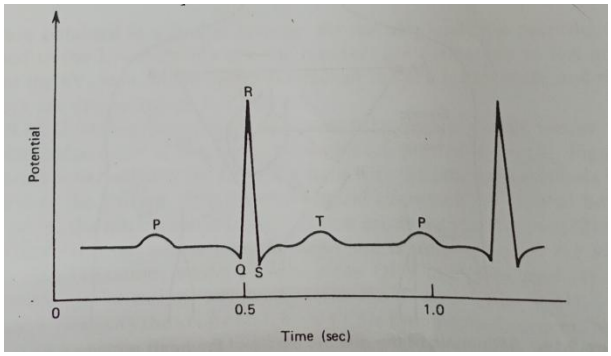



Figure 10

Figure 11 shows the six frontal plane ECGs for a normal subject. Note that in some cases the waveform is positive and in other cases it is negative; the sign of the waveform depends upon the direction of the electric dipole vector and the polarity and position of the electrodes of the measuring instrument.

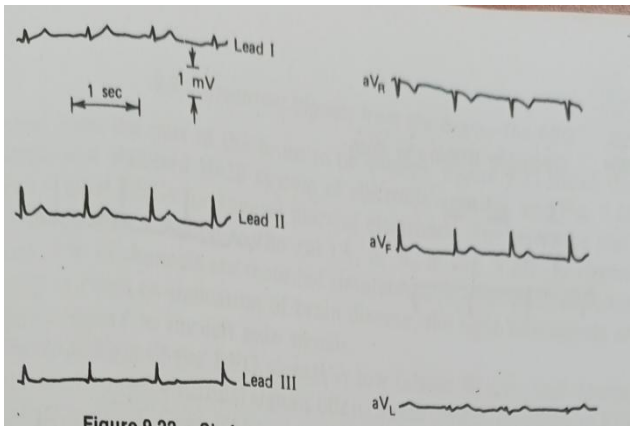



Figure 11

In a clinical examination, six transverse plane ECGs are usually made in addition to six frontal plane ECGs. For the transverse plane measurement the negative terminal of the ECG recorder is attached to an indifferent electrode at the center point of the three resistors connected to RA, LL, and LA (Fig. 12 a), and the other electrode is moved across the chest wall to the six different position shown in Fig. 12. Figure 13 shows typical transverse plane ECGs.

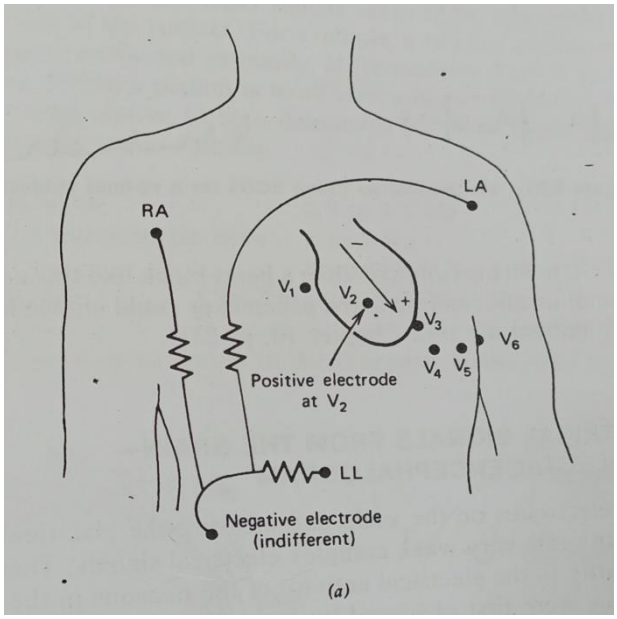


Figure 12 a

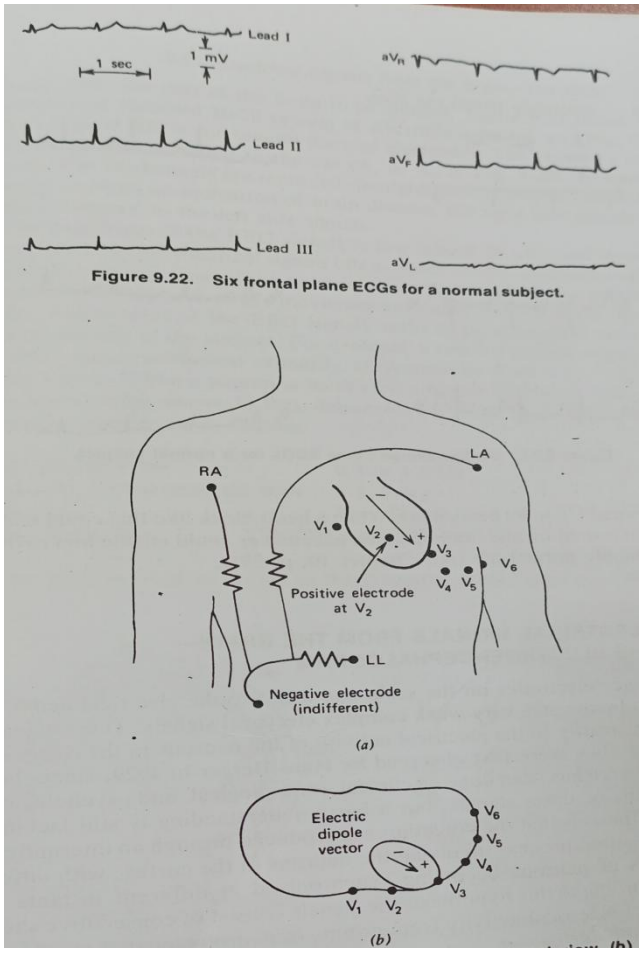



Figure 12

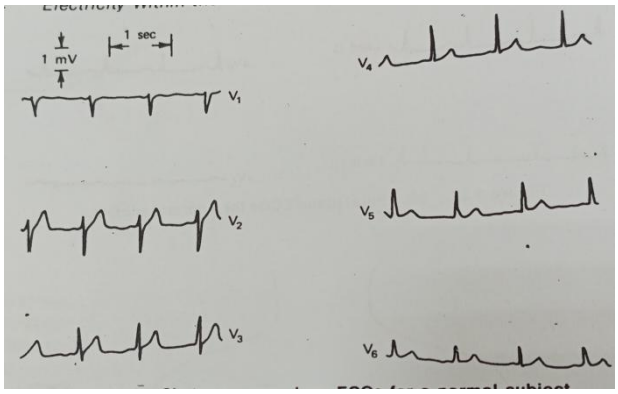



Figure 13

As ECG shows disturbances in the normal electrical activity of the heart. For example, an ECG may signal the presence of an abnormal condition known as heart block. If the normal SA node signal is not conducted into the ventricle, then a pulse from the AV node will control the heartbeat at a frequency of 30 to 50 beats/min,

which is much lower than normal (70 to 80 beats/min). While a heart block like this could make a patient a semi-invalid, an implanted pacemaker could enable him to live a reasonably normal life.

## The electroencephalogram (electrical signals from the brain)

If you place electrodes on the scalp and measure the electrical activity, you will obtain some very weak complex electrical signals. These signals are due primarily to the electrical of the neurons in the cortex of the brain. One hypothesis is that the potentials are produced through an intermittent synchronization process involving the neurons in the cortex, with different groups of neurons becoming synchronized at different instants of time. According to this hypothesis the signals consist of consecutive short segments of electrical activity from groups of neurons located at various places on the cortex.

The recording of the signals from the brain is called the electroencephalogram (EEG). Electrodes for recording the signals are often small discs of chloride silver. They are attached to the head at locations that depend upon the part of the brain to be studied. Figure 14 shows the international standard 10-20 system of electrode location, and Fig. 15 shows typical EEGs for several pairs of electrodes. The reference electrode is usually attached to the ear ($A_1$ or $A_2$ in Fig 14). In routine exams, 8 to 16 channels are recorded simultaneously. Since asymmetrical activity is often an indication of brain disease, the right side signals are often compared to the left side signals.

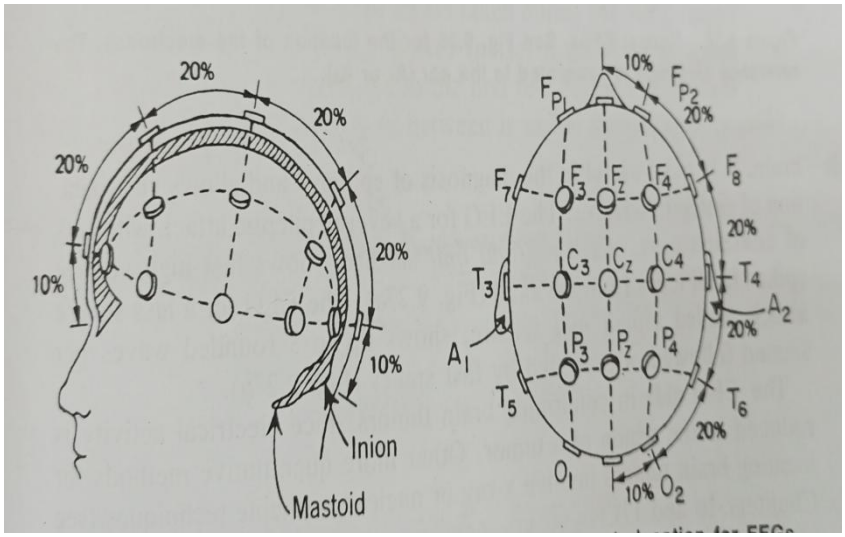



Figure 14

The amplitude of the EEG signals is low (about 50 **μ**V), and interference from external electrical signals often causes serious problems in EEG signals processing. Even if the external noise is controlled, the potentials of muscle activity such as eye movement can cause artifacts in the record.

The frequencies of the EEG signals seem to be dependent upon the mental activity of the subject. For example, a relaxed person usually has an EEG signal composed primarily of frequencies from 8 to 13 Hz, or alpha waves. When a person is more alert a higher frequency range, the beta wave range (above 13 Hz), dominates the EEG signal. The various frequency bands are as follows:

| | |
|---|---|
| Delta (**δ**), or slow | 0.5 to 3.5 Hz |
| Theta (**θ**), or intermediate slow | 4 to 7 Hz |
| Alpha (**α**) | 8 to 13 Hz |
| Beta (**β**), or fast | greater than 13 Hz |

The EEG is used as an aid in the diagnosis of diseases involving the brain. It is most useful in the diagnosis of epilepsy and allows classification of epileptic seizures. The EEG for a severe epileptic attack with loss of consciousness, called a grand mal seizure, shows fast high voltage spikes in all leads from the skull (Fig. 15a). The EEG for a less severe attack, called a petit mal seizure, shows up to 3 rounded waves per second followed or preceded by fast spikes (Fig.15b).

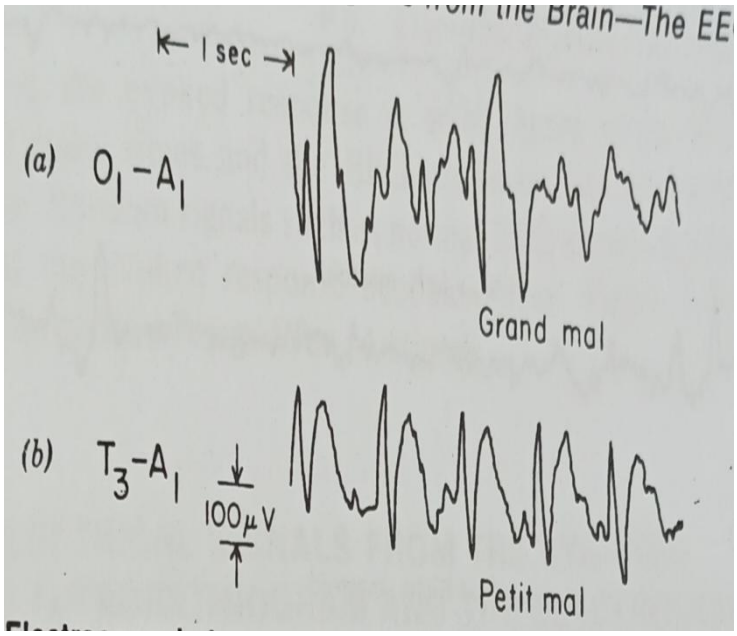


Figure 15

The EEG aids in confirming brain tumors since electrical activity is reduced in the region of a tumor. Other more quantitative methods for locating brain tumors involve x-ray or nuclear medicine techniques.

The EEG is used as a monitor in surgery when the ECG cannot be used. It is also useful in surgery for indicating the anesthesia level of the patient. During surgery a signal channel is usually monitored.

Much research on sleep involves observing the EEG patterns for various stages of sleep (Fig. 16). As a person becomes drowsy, particularly with his eyes closed, the frequencies from 8 to 13 Hz (alpha waves) dominate the EEG. The amplitude increases and the frequency decreases as a person moves from light sleep to deeper sleep. Occasionally an EEG taken during sleep shows a high frequency pattern called paradoxical sleep or rapid eye movement (REM) sleep because the eyes move during this period. Paradoxical sleep appears to be associated with dreaming.

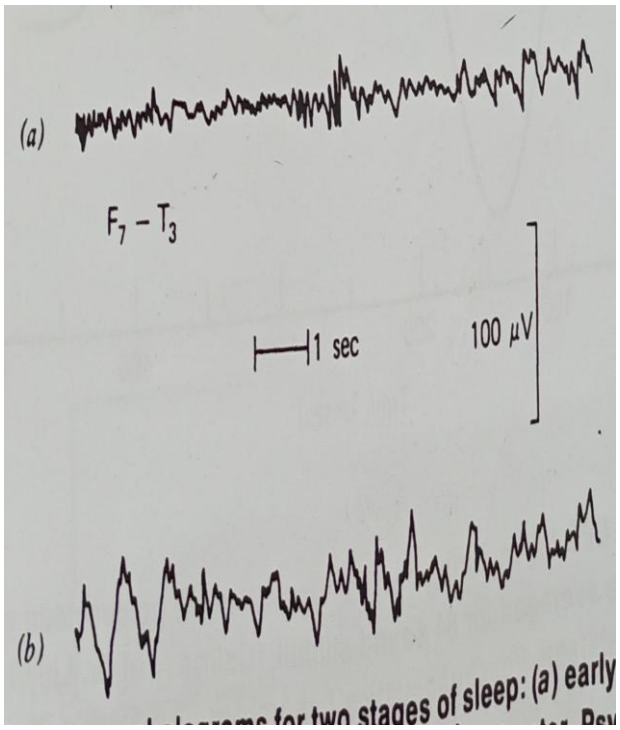


Figure 16

Besides recording the spontaneous activity of the brain, we can measure the signals that result when the brain receives external stimuli such as flashing lights or pulses of sound. Signals of this type are called evoked responses. Figure 17a shows three EEGs taken during the early stages of sleep with a series of 10 sound pulses (noise) used as an external stimulus. The EEGs show responses to the first few pulses and the last two pulses. The lack of responses in between is called habituation.

Because the evoked response is small, quite often the stimulus is repeated many times and the EEG responses are averaged in a small computer. Random signals such as normal EEG signals tend to average to zero and the evoked response becomes clear. Figure 17b shows an evoked response averaged for 64 stimuli.

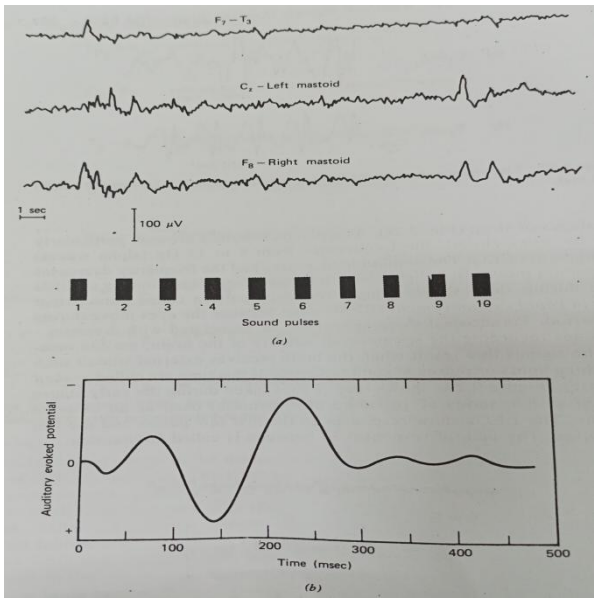

$F_7 - T_3$
$C_z$ – Left mastoid
$F_8$ – Right mastoid
1 sec
100 μV
1
2
3
4
5
6
7
8
9
10
Sound pulses
(a)
Auditory evoked potential
–
0
+
0
100
200
300
400
500
Time (msec)
(b)

Figure 17

# Energy, Work and power of the body

**All body activities including thinking, doing work, or keeping the body temp. constant involve energy changes, for example under resting(Basal)conditions the skeletal muscles and the heart using 25% of the body's energy ,another 19%is being used by the brain,10%is being used by the kidneys, and 27% is being used by the liver and the spleen. A small percent of about 5% of food energy being excreted in feces and urine.**

**Extra food energy will be stored mainly as fat. External heat energy from environment can help maintain the body temp. , but it has no use in body function.**

## Conservation of energy

**Change in the stored energy** (i.e. food energy, body fat and the body heat)

**=Heat lost from the body + Work done**

Assumes that no food or drink is taken and no feces or urine is excreted during the interval of time considered.

- **This is similar to the first law of thermodynamic:-**

$$\Delta Q = \Delta u + \Delta w$$

- Where ΔQ is the change of quantity of heat of the system.
- Δu is the change in the internal or stored energy.
- Δw is the work done.

This can be written as

$$\Delta u = \Delta Q - \Delta w$$

A body doing no work (Δw=0) and at constant temp. continues to lose heat to its surroundings, and ΔQ is negative. Therefore, Δu is also negative, indicating a decrease in stored energy.

The rate of change of their variables is just taken per unit time ( by dividing on Δt) .

$$\Delta u / \Delta t = \Delta Q/\Delta t - \Delta w/\Delta t$$

The body's basic source of energy is the food energy; it must be chemically changed by the body to make molecules that can combine with oxygen in the body's cells.

## Energy change in the body

The units are joule or calorie 1cal= 4.184J or 1Kcal=4184J

The power is defined as energy or work per unit time =J/s=watt.

In the oxidation process within the body, heat is produced as energy of metabolism. The rate of oxidation is called metabolic rate.

For example the oxidation of one mole of glucose can be shown as:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6H_2O + 6CO_2 + 686Kcal$$

| 1 mole | 6 mole | 6 mole | 6 mole |
|---|---|---|---|
| 180g | 192g | 108g | 264g |

$Co_2$ and $O_2$ are gases ( 1 mole of a gas at normal temp. and pressure has a volume 22.4 liters)

From the above equation we can calculate useful quantities for glucose metabolism:

- Kcal of energy released/g of fuel (glucose) =686/180=3.8
- Kcal of energy released/L of $O_2$ used=686/ (22.4×6) =5.1
- Liters of $O_2$ used/g of fuel glucose = (22.4×6)/180=0.75
- Liters of $Co_2$ produced /g of fuel glucose= (22.4×6)/180=0.75

So the ratio of moles of $Co_2$ produced to moles of $O_2$ used, called the (respiratory quotient) R=1 ⟶ No. of moles of $Co_2$/No. of moles of $O_2$ =1

Similar calculation can be done for fats, proteins, and other Carbohydrates.

By measuring the energy released per liter of $O_2$ we can get a good estimation of the energy released. Table 5.1 shows the caloric values for different types of foods and fuels. It gives the maximum

values expected because not all food energy is available, as part of it is lost in incomplete combustion (not metabolized).

Table 5.1. Typical Energy Relationships for Some Foods and Fuels

| Food or Fuel | Energy Released per Liter of $O_2$ Used (kcal/liter) | Caloric Value (kcal/g) |
|---|---|---|
| Carbohydrates | 5.3 | 4.1 |
| Proteins | 4.3 | 4.1 |
| Fats | 4.7 | 9.3 |
| Typical diet | 4.8–5.0 | — |
| Gasoline | — | 11.4 |
| Coal | — | 8.0 |
| Wood (pine) | — | 4.5 |

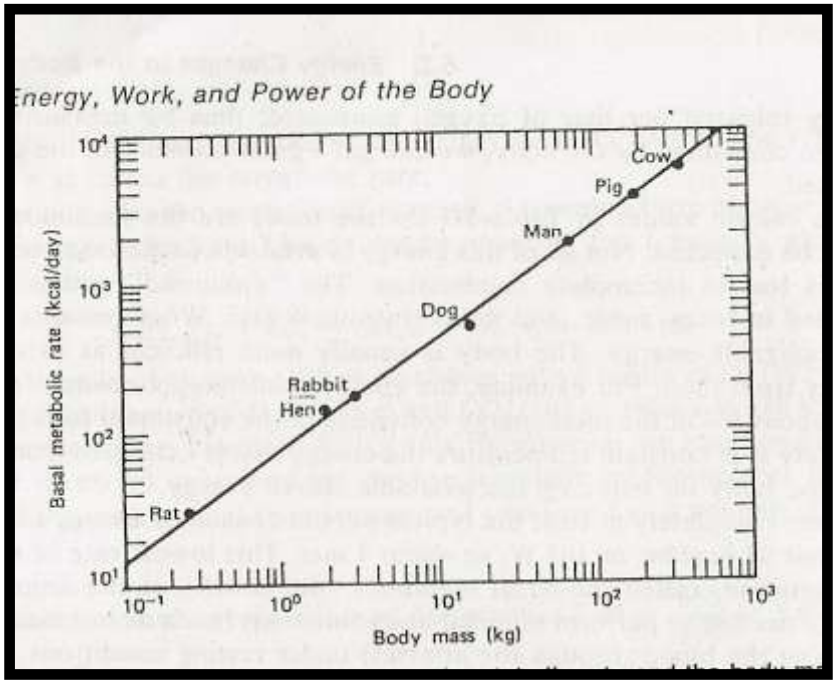
When the body is completely at rest, it will have the lowest rate of energy consumption this is called the basal metabolic rate (BMR), which is the amount of energy needed to perform minimal body functions (such as breathing and pumping the blood through the arteries) under resting conditions, and for typical person 92 Kcal/hr ≈ 107w or about 1 met (met is 50 Kcal/$m^2$hr).

$m^2$: body surface area

BMR depends on sex, age, height, and weight; it depends primarily on thyroid function, overactive thyroid gives higher BMR.

Since the energy used for basal metabolism becomes heat which is mainly dissipated from the skin, so the basal rate is related to the surface area or to the mass of the body. In figure 5.1 the graph

represents the change between BMR (kcal/day) and the mass of different animals, the slope of the graph indicates that the BMR is proportional to mass.




When the animals gets larger the BMR increases faster than their increases in surface area but BMR increases even more faster with their mass(volume).

The BMR depends to large extent on the body temp., for an increase of 1°C it will change by 10% in the metabolic rate, so for 3°C the change will be 30% greater than normal. Similarly ,if the body temp. drops 3°C below normal, the metabolic rate decreases by about 30%. For this reason hibernating animals at low body temp. will reduce the metabolic rate very much.

- A man who is taking food energy equivalent to his BMR plus his other physical activities will keep on constant weight.
- Less food will cause weight lose and for longer time cause <u>starvation</u>.
- Excess food of body needs will cause food storage and increase in weight.
- BMR is sometimes determined from oxygen consumption when resting, we can also estimate the food energy used in various physical activities by measuring the oxygen consumption, table (5.2) shows some typical values for various activities.

Table 5.2. Oxygen Cost of Everyday Activities for a Man with a Surface Area of 1.75 $m^2$, Height of 175 cm, and Mass of 76 kg[a]

| Activity | $O_2$ Consumption (liters/min) | Equivalent Heat Production | | Energy Consumption (mets—50 kcal/$m^2$ hr) |
|---|---|---|---|---|
| | | kcal/min | W | |
| Sleeping | 0.24 | 1.2 | 83 | 0.82 |
| Sitting at rest | 0.34 | 1.7 | 120 | 1.15 |
| Standing relaxed | 0.36 | 1.8 | 125 | 1.25 |
| Riding in automobile | 0.40 | 2.0 | 140 | 1.35 |
| Sitting at lecture (awake) | 0.60 | 3.0 | 210 | 2.05 |
| Walking slow (4.8 km/hr) | 0.76 | 3.8 | 265 | 2.60 |
| Cycling at 13–17.7 km/hr | 1.14 | 5.7 | 400 | 3.90 |
| Playing tennis | 1.26 | 6.3 | 440 | 4.30 |
| Swimming breaststroke (1.6 km/hr) | 1.36 | 6.8 | 475 | 4.65 |
| Skating at 14.5 km/hr | 1.56 | 7.8 | 545 | 5.35 |
| Climbing stairs at 116 steps/min | 1.96 | 9.8 | 685 | 6.70 |
| Cycling at 21.3 km/hr | 2.00 | 10.0 | 700 | 6.85 |
| Playing basketball | 2.28 | 11.4 | 800 | 7.80 |
| Harvard Step Test[b] | 3.22 | 16.1 | 1120 | 11.05 |

[a]Adapted from P. Webb, in J. F. Parker and V. R. West (Eds.), *Bioastronautics Data Book*, National Aeronautics and Space Administration, Washington, D.C., 1973, pp. 859–861.
[b]A test in which the subject steps up and down a 40 cm step 30 times/min for 5 min.

**Example: Suppose you wish to lose 4.54kg either through physical activity or by dieting.**

**1-How long would you have to work at an activity of 15Kcal/min to lose 4.54kg of fat?**

**From table 5.1 maximum of 9.3kcal/g of fat, if you worked for T minutes, then**

$$T(15kcal/min)=(4.54x10^3g)(9.3kcal/g)=4.2x10^4kcal$$

$$T=2810\ min\approx47hr$$

**2- It is much easier to lose weight by reducing your food intake. If you normally use 2500kcal/day, how long must you diet at 2000kcal/day to lose 4.54kg of fat?**

**T= (energy of 4.54kg fat/energy deficit per day) $4.2X10^4kcal$ / $5x10^2kcal/day$ ≈ 84 days**

**Table 5.3 gives oxygen consumption for various organs, some organs use rather large amount of energy ,the kidney uses more energy per kilogram than the heart.**

**Table 5.3. Oxygen Use and Metabolic Rate Contribution of the Principal Organs of a Resting, Healthy Man Weighing 65 kg[a]**

| Organ | Mass (kg) | Average Rate of $O_2$ Consumption by Experiment (ml/min) | Average Rate of Energy Consumed (kcal/min) | Power per kg (kcal/min/kg) | Percent of BMR |
|---|---|---|---|---|---|
| Liver and spleen | — | 67 | 0.33 | — | 27 |
| Brain | 1.40 | 47 | 0.23 | 0.16 | 19 |
| Skeletal muscle | 28.0 | 45 | 0.22 | $7.7 \times 10^{-3}$ | 18 |
| Kidney | 0.30 | 26 | 0.13 | 0.42 | 10 |
| Heart | 0.32 | 17 | 0.08 | 0.26 | 7 |
| Remainder | — | 45 | 0.23 | — | 19 |
| | | 250 | 1.22 | | 100% |

[a]Adapted from R. Passmore, in R. Passmore and J.S. Robson (Eds.), *A Companion to Medical Studies*, Vol. I, Blackwell, Osney Mead, England, 1968, p. 4.9.

## Work and power

Chemical energy stored in the body is converted into external mechanical work as well as into life-preserving functions.

Mechanical work is usually defined by $\Delta w = F.\ \Delta x$ where F is the force on the same line of displacement x, or it can be also written as:

$(\Delta w = F\ \Delta x \cos \Theta)$ where Θ is the angle between F and the direction of movement, the power is work per unit time.

$P = \Delta w / \Delta t = F\ \Delta x / \Delta t = F\ v$ where v is the velocity

When the force is perpendicular to the displacement work will be zero, such as walking body, his weight is perpendicular to distance of movement but practically it will not be zero because the uses energy against friction and other movement of his body, but in the case of climbing person for distance (h) the weight is on the same line of displacement then the work = mgh, the efficiency of human body is

E = work done/ energy consumed

Efficiency is usually lowest at low power but can increase to 20% for trained individuals in activities such as cycling and rowing.

The maximum work capacity of the body is variable, for short period of time the body can perform at very high power levels,(like running very fast but it is more limited for longer periods).It is found

that long term power is proportional to the maximum rate of oxygen consumption in the working muscles.

**For healthy man this consumption is 50ml/kg m of body weight each minute. The body can supply an instantaneous energy for short term power needs, this can be done by splitting energy rich-phosphates and glycogen leaving an oxygen deficit in the body. This process can only last about a minute and is called anaerobic(without oxygen) .For longer term work requires oxygen aerobic. Fig (5.3)**

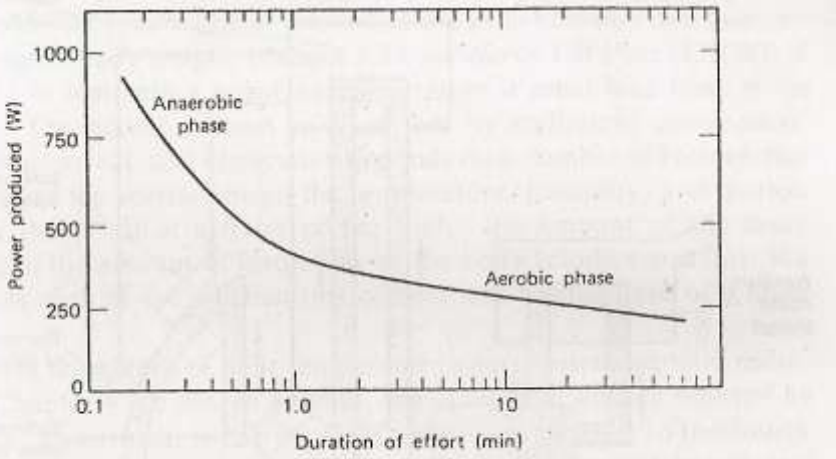



Figure 5.3. Typical power output on a bicycle versus duration of effort for an average healthy adult. Anaerobic work can only be maintained about 1 min.

## Heat loses from the body

(Homeothermic)(Warm-blooded) such as birds and mammals, (poikilothermic)(cold-blooded) such as frog and snake, will have a higher body temp. on a hot day than mammals, birds and mammals

both have mechanisms to keep their body temp. constant despite fluctuations in the environmental temp. Constant body temp. permit metabolic processes to produce at constant rates and these animals to remain active even in cold climates.

**The normal human temp. is 37°C which is obtained from taking the temp. of large # of people. For a single individual the body temp. may vary about ≈0.5°C.The rectal temp. is about 0.5°C higher than the oral temp.**

**The temp. of the body depends on the:**

1-Time of the day (lower in the morning)

2- Environment temp.

3-The amount of clothing

4-Health of the person

5- On his recent physical activity.

- **For example rectal temp. after hard exercise may be as high as 40°C ,the body losses heat mainly by radiation, convection, and evaporation, all these processes can take place in the skin. The evaporation of perspiration from the skin can cool down the skin by absorbing the latent heat of evaporation from it.**

Evaporation takes place also in breathing causing cooling effect. If the air is cold it will also cool down the body. Eating and drinking cold or hot food can also decrease or increase the body temp.

The body temp. is kept constant for this reason the hypothalamus in the brain can control the body temp. (thermostate like).After heavy exercise the body is heated the hypothalamus initiate the sweating and vasodilation is the first causes heat loss by evaporation and the second increasing the blood supply to the skin for more loss of heat. On the other hand if the environment temp. drops the thermo receptors on the skin signals to the hypothalamus which in turn induce shivering to increase the body temp.

The production of heat in the body for 2400 Kcal/day (assumeing no change in body weight)=1.7Kcal/min=120J/sec =120W.

So the body must lose the same amount of heat to stay at constant temp. .The heat loses depends on many factors:

1- The temp. of the surroundings

2-Humidity

3-Motion of the air

4-The physical activity of the body

5-The amount of the body exposed

6-The amount of the insulation of the body (like clothes and fat)

## Transfer of heat by radiation

**All objects regardless on their temp. emit electromagnetic radiation, the amount of energy emitted by the body is proportional to the absolute temp. raised to the fourth power. The body also receives radiant energy from surrounding objects. The amount of heat difference between the energy radiated by the body and the energy absorbed from the surrounding can be calculated from the equation:**

$$H_r = K_r A_r e (T_s - T_w)$$

**Where**

$(H_r)$ **is the rate of heat energy loss or gain**

$(K_r)$ **is a constant depends upon various physical parameters and it's about =5Kcal/m$^2$ hr C° for man**

$(A_r)$ **effective body surface area emitting radiation**

**e is the emissivity of the surface which is nearly=1,independent on the color of the skin indicating that the skin at this wavelength is almost a perfect emitter and absorber of radiation.**

$(T_s)$ **is the skin temp. in C°**

**($T_w$) is the temp of the surrounding walls**

**$\Delta$ Heat losses by radiation occur even the temp. differences is not high.**

**Example: for a nude person have a skin temp. 34°C in a room of walls temp. 25°C and his body area 1.2$m^2$ will lose 54 Kcal/hr which is 54% of the total losses. Most of the remaining heat will be by convection.**

## Transfer of heat by convection

**Heat losses by convection ($H_c$)**

$$H_c = K_c A_c (T_s - T_a)$$

**Where**

**$H_c$ is the amount of heat gained or lost be convection**

**$A_c$ is the effective surface area**

**$T_s$ is the skin temp.**

**$T_a$ is the environment temp. or air temp.**

**$K_c$ is a constant that depends on the movement of the air, for a resting body and no apparent wind $K_c$ is about 2.3kcal/ $m^2$ hr °C.**

**When the air is moving $K_c$ increases according to the equation:-**

$$K_c = 10.45 - v + 10\sqrt{v}$$ where v is the wind speed in m/sec

This equation is valid for speeds between 2.23m/sec (5mph) and 20m/sec (45mph) (1 mile=1.6 km).

The equivalent temp. due to moving air is called the wind chill factor and is determined by the actual temp. and wind speed. For example for a windy day speed 10 m/sec an-20°C has the same cooling effect on the body as -40°C on a calm day. Table (5.5)

## Transfer of heat by evaporation

Under normal temp. conditions and in the absence of hard work or exercise, heat loss mainly by radiation and convection, losses by evaporation become of less importance. Under extreme conditions of heat and exercise, a man may sweat more than 1 litter of liquid per hour. Since each gram of water that evaporate carries with it the heat of vaporization of 580 calories, the evaporation of I liter carries with it 580kcal. There is some heat losses by perspiration even if the body does not feel sweaty, it amount to about 7Kcal/hr, equivalent to 7% of the body losses. A similar loss of heat is due to the evaporation of moisture in the lungs, an additional amount of water will be evaporated during expiration. This will cool the body the same as the evaporation from the skin, also when we inspire cold air inside the lungs which also cool down the body. Under typical conditions The total respiratory heat losses is about 14% of the body's heat loss.

Under extreme condition of heat and exercise the sweat evaporation is very important, a man may sweat more than 1 lit/hr, this is if all sweat is evaporated, the un evaporated part (running down)does not contribute with cooling.

## Counter current heat exchange

Since the radiation of heat from the body and the transfer of heat to the air depend upon the skin temp., any factors that affect the skin temp. also affect the heat loss. The body has the ability to select the path returning blood from the hands and feet. In cold weather blood is returned to the heart through internal veins that are in contract to the arteries carrying blood to the extremities (hands and feet).In this way some of the heat from the blood going to the extremities is used to heat thee returning blood. This counter current heat exchange lowers the temp. of the extremities and reduces heat loss from the body to the environment.

In warm weather the returning venous blood runs near the skin surface raising the skin temp. and thus increasing the heat loss from the body.

Most of the previous study involved heat losses from a nude person, if we consider the clothes, the calculation become more

**complicated, for this reason another unit of clothing is the (clo) is being introduced. One (clo) corresponds to the insulating value of clothing needed to maintain a subject sitting at rest in comfort in a room at 21°C and air movement of 0.1m/sec and humidity of less than 50%.**

**One (clo) is equivalent to lightweight suit an individual in the arctic needs clothing of insulation of 4 clos.**

**(A fox fur has an insulating value of 6 clos).**

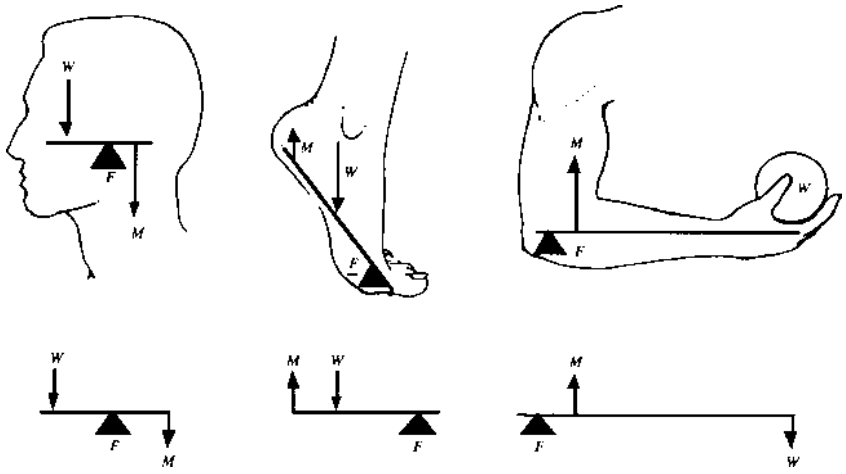
# Force on & in body

# Statics

Forces involved with muscles, bones, and tendons discussed.

When objects are stationary (static) they are in a state of equilibrium the sum of the forces in any direction is equal to zero, and the sum of the torques about any axis also equals zero.

Many of the muscle and bone systems of the body act as levers. Levers are classified as first-, second-, and third-class systems (Fig. 1). Third-class levers are most common in the body, Second-class levers are next in number, and first-class levers are least common.




First class Second class Third class

Figure. 1 The three lever classes and schematic examples of each in the body.

**W** is a force that could be **the weight**, **F** is the force at the **fulcrum point**, and **M** is the **muscle force.**

A simple example of a lever system in the body is the case of the biceps muscle and the radius bone acting to support a weight W in the hand ( Fig. 2a). Figure 2b shows the forces and dimensions of a typical arm.

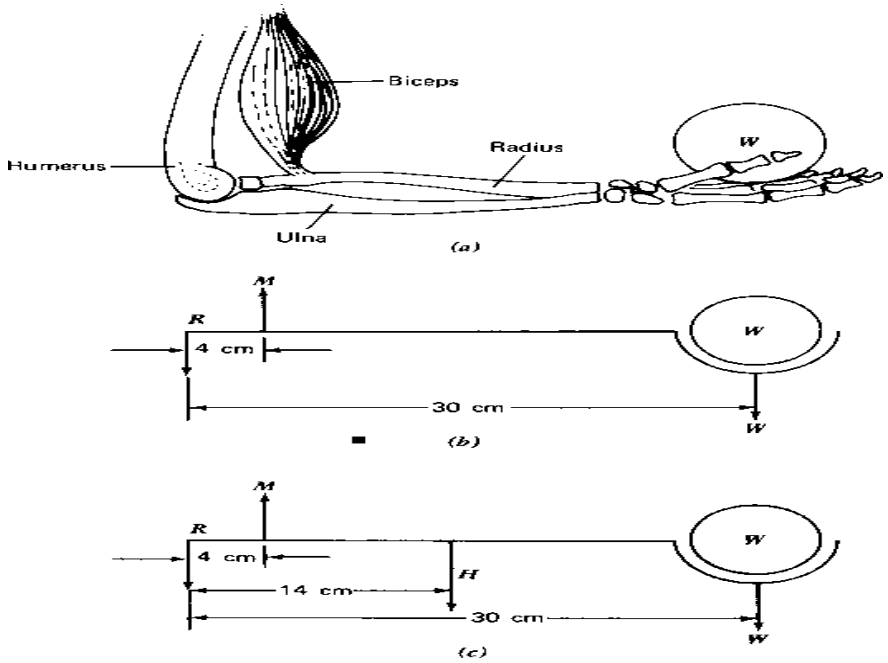



Figure 2. The forearm. (a) The muscle and bone system. (b) The forces and dimensions: R is the reaction force of the humerus on the ulna, M is the muscle force supplied by the biceps, and W is the weight in the hand. (c) The forces dimensions where the weight of the tissue and bones of the hand and arm H is included and located at their center of gravity.

We can find the force supplied by the biceps if we sum the torques about the pivot point at the joint. There are only two torques: that due to the weight W, which is equal to 30W acting clockwise, and that produced by the muscle force M, which is counterclockwise and of magnitude 4M. With the arm in equilibrium we find that 4M-30W=0 and M=7.5W or that a muscle force 7.5 times the weight is needed.

In figure 2c shows a more correct representation of the problem with the weight of the forearm and H hand included. By summing the torques about the joint we obtain M=3.5H+7.5W, which simply means that the force supplied by the muscle must be larger than that indicated by our first calculation ( Fig. 2b).

Let us now consider the effect on the muscle force needed as the arm changes its angle as shown in Fig. 3a. Figure 3b shows the force we must consider for an arbitrary angle α. If we take the torques about the joint we find that M remains constant as α changes! However, the length of the biceps muscle changes with the angle.

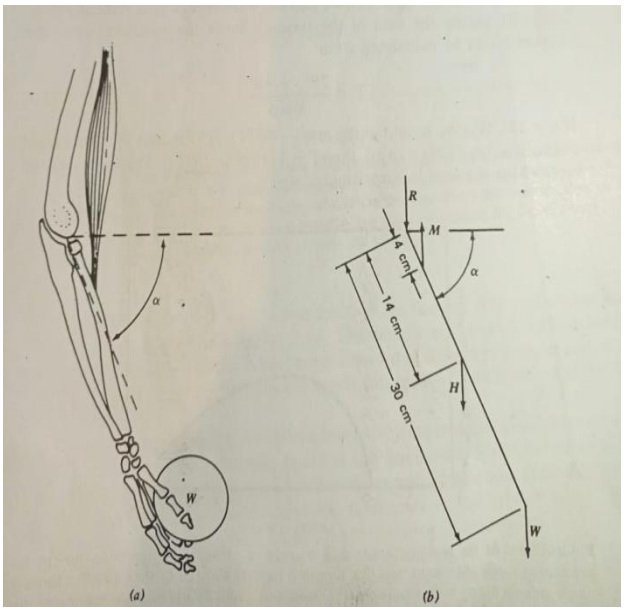



Figure 3

The arm can be raised and held out horizontally from the shoulder by the deltoid muscle (Fig. 4a); we can show the forces schematically ( Fig. 4b ). By taking the sum of the torques about the shoulder joint, the tension T can be calculated from

$$T = \frac{2W_1 + 4W_2}{sin\alpha}$$

If $\alpha=16^{\circ}$, $W_1$=68 N and $W_2$=45N, then T=1145 N. The force needed to hold up the arm is surprisingly large.

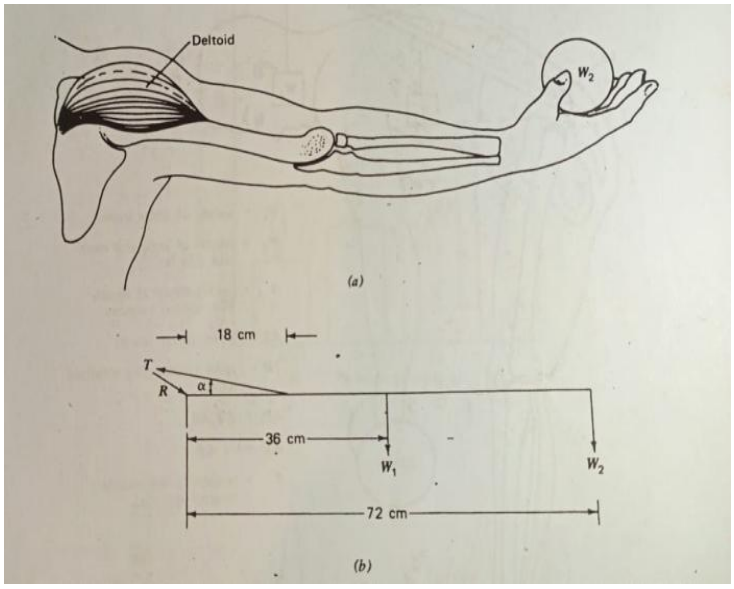



Figure 4

An often abused part of the body is the lumbar (lower back ) region, shown

schematically in Fig. 5a. The calculated force at the fifth lumbar vertebra (L5) with the body tipped forward at 60° to the vertical and with a weight of 225 N in the hands can approach 3800 N ( Fig. 5b ).

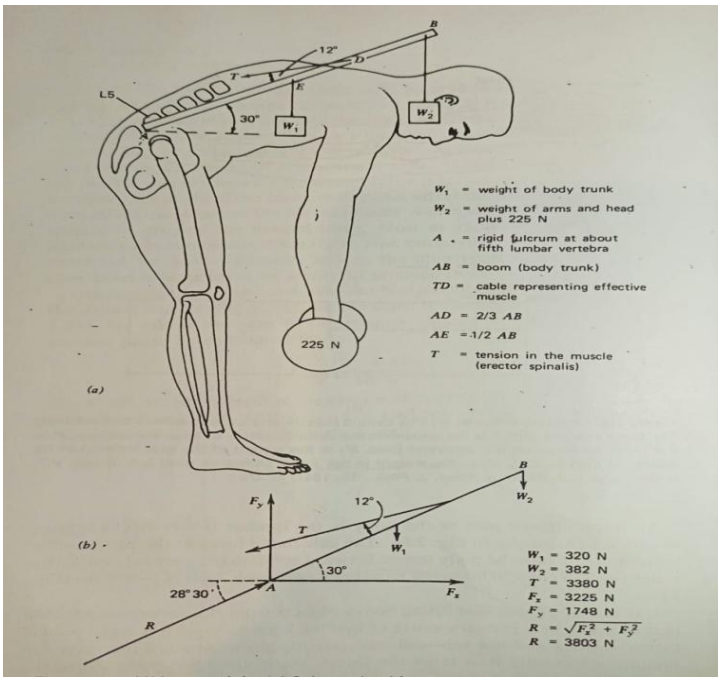



Figure 5

Sometimes of the greatest forces in the body occur at the patella. When a person is squatting, the tension in the tendons that pass over the patella may be more than two times his weight (Fig. 6 )

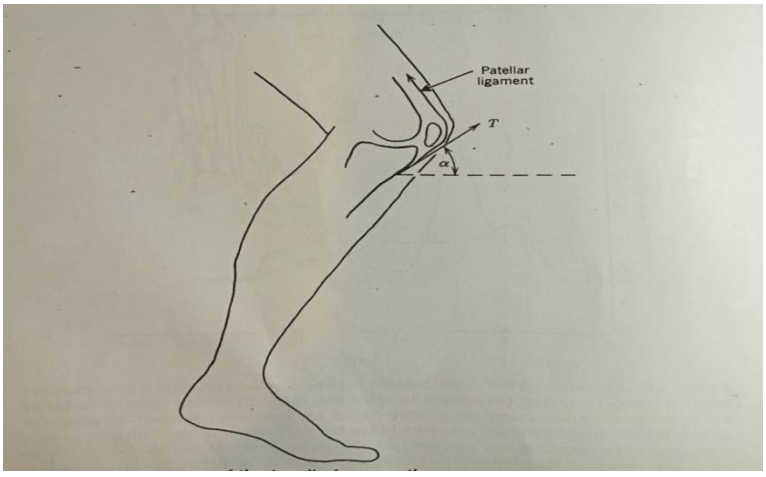



Figure 6

## Frictional forces

In the body, friction effects are often important. When a person is walking, as the heel of the foot touches the ground a force is transmitted from the foot to the ground ( Fig. 7a ). We can resolve this force into horizontal and vertical components. The vertical reaction force is supplied by the surface and is labeled N (a normal force). The horizontal reaction component must be supplied by frictional forces. The maximum force of friction f is usually described by

$$f = \mu N$$

where N is a normal force and μ is the coefficient of friction between the two surfaces. The value of μ depends upon the two materials in contact, and it is essentially independent of the surface area.

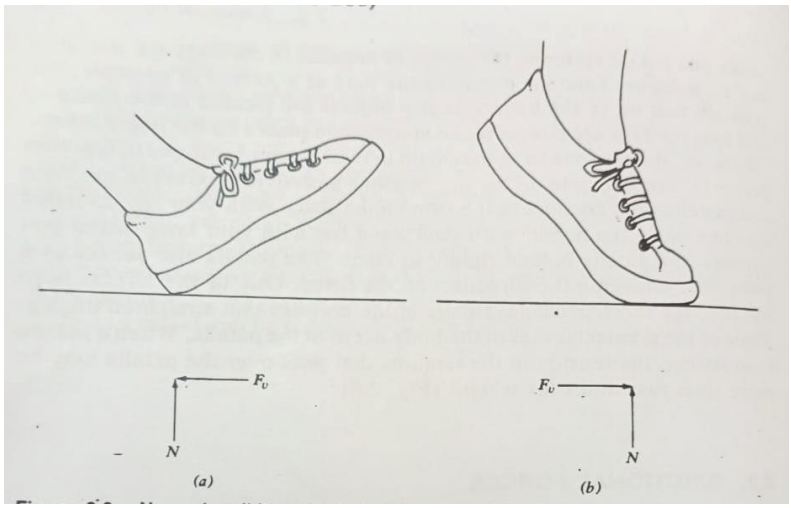



Figure 7

In general, the frictional force is large enough both when the heel touches down and when the toe leaves the surface ( Fig. 7b ) to prevent a person from slipping. Occasionally, a person is on an icy, wet, or oily surface where μ is less than 0.15 and his foot slips.

The coefficient of friction in bone joints is usually much lower than in engineering-type materials. If a disease of the joint exists, the friction may become large. The synovial fluid in the joint is involved in the lubrication.

The saliva we add when we chew food acts as a lubricant. The heart, lungs and intestines are lubricated by a slippery mucus covering to minimize friction.

## Dynamics

Let us now examine forces on the body where acceleration or deceleration is involved; for simplicity, we will usually consider cases in which the acceleration or deceleration is constant. If we limit ourselves to one dimensional motion, then Newton's law, force equals mass times acceleration, can be written without vector notation as

$$F = ma$$

This is not the way Newton originally wrote the law; he said force equals the change of momentum Δ(mv) over a short interval of time Δt or

$$F = \frac{\Delta(mv)}{\Delta t}$$

Accelerations can produce a number of effects such as

1. An apparent increase or decrease in body weight
2. Changes in internal hydrostatic pressure
3. Distortion of the elastic tissues of the body
4. The tendency of solids with different densities suspended in a liquid to separate.

We have thus far concerned ourselves with linear acceleration and deceleration. If we subject the body to oscillatory motion, resonance behavior can occur. Each of our major organs has its own resonant frequency depending on its mass and the elastic forces that act on it. Pain or discomfort occurs in a particular organ if it is vibrated at its resonant frequency.

The centrifuge is a way to increase apparent weight. It is especially useful for separating a suspension in a liquid. It speeds up the sedimentation that occurs at a slow rate under the force of gravity.

Let us consider first sedimentation of small spherical objects of density ρ in a solution of density $\rho_\circ$ in a gravitational field g. We know that falling objects reach a maximum (terminal) velocity due to viscosity effects. Stockes has shown that for a spherical object of radius a, the retarding force $F_d$ and terminal velocity ν are related by

$$F_d = 6\pi a\eta v$$

where η is the viscosity of the liquid through which the sphere is passing.

When the particle is moving at s constant speed, the retarding force is in equilibrium with the difference between the downward gravitational force and the upward buoyant force ( the weight of the liquid the particle displaces). Thus we have:

1. The force of gravity $F_g = \frac{4}{3}\pi a^3 \rho g$
2. The buoyant force $F_B = \frac{4}{3}\pi a^3 \rho_\circ g$
3. The retarding force $F_d = 6\pi a\eta v$

$F_g$ acts downward and $F_B$ acts upward, and the difference is equal to $F_d$.

From $F_g - F_B = F_d$ we obtain the expression for the terminal velocity (sedimentation velocity),

$$v = \frac{2a^2}{9\eta} g(\rho - \rho_\circ) \ldots\ldots\ldots\ldots\ldots (1)$$

Equation 1 is valid only for spherical particles; however, we can use it as a guide to the behavior of particles with a more complicated shape.

## Gravitational force

Newton formulated the law of universal gravitation. This law states that there is a force of attraction between any two objects; our weight is due to the attraction between the earth and our bodies.

## Electrical force

The forces produced by muscles are caused by electrical charges attracting or repelling other electrical charges. Each of the billions of living cells in the body has an electrical potential difference across the cell membrane because of a difference in charge between the inside and outside of the cell.

## Forces on teeth

Forces on teeth arise from several sources. Figure 8 shows how the masseter muscles provide the force in the lever system involved in chewing and biting. Lever models can be used to examine the quasistatics of chewing and biting.

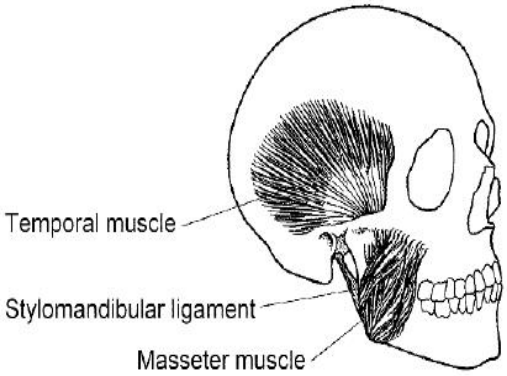



Figure 8

## The physics in orthodontics

Orthodontics is the practical application of biomechanics to move teeth using forces applied by *appliances*, such as wires, brackets, and elastics. Each tooth has a center of mass, but since teeth are not free bodies –they are restrained by the periodontium – a more useful position in the tooth is defined, the *center of resistance*. This is the balance point for the tooth.

Figure 9 shows how forces and torques (moments) applied to the crown of a tooth, can be designed to create a lateral force at the center of resistance, but no torque about it. Appliances can affect several teeth, such as the intrusion

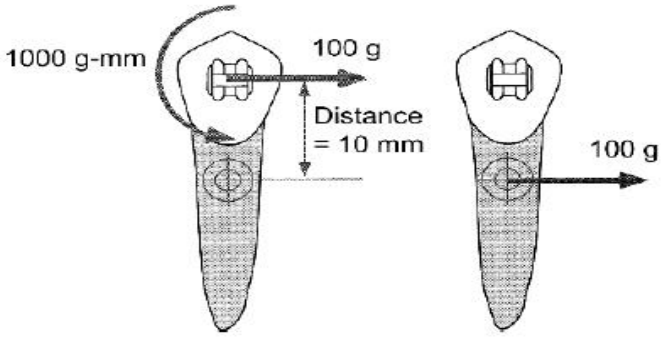



Figure 9

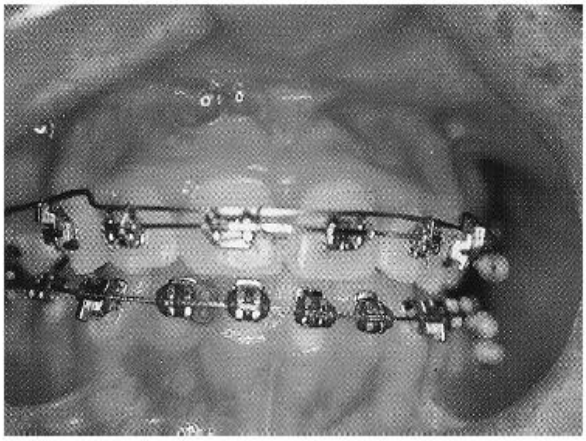


Figure 10

arch shown in Fig. 10, which leads to the application of forces and torques shown in Fig. 11.

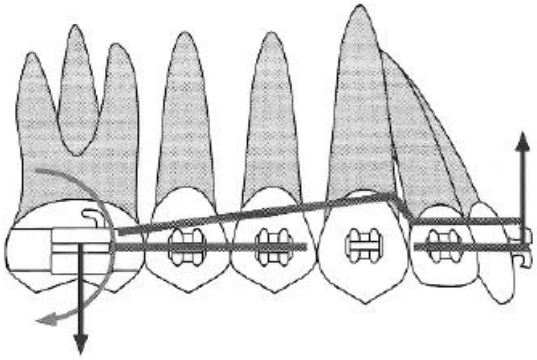


Figure 11

# Heat and Cold in Medicine

## Temperature scales

Temperature is difficult to measure directly, so we usually measure it indirectly by measuring one of many physical properties that change with temperature.

In the United States the most common temperature scale is the **Fahrenheit ( $^{\circ}$F )** scale. Water freezes at 32 $^{\circ}$F and boils at 212 $^{\circ}$F, and the normal body temperature (rectal ) is about 98.6 $^{\circ}$F.

Most scientists in the United States use the **Celsius ( °C )** scale ( formerly called the centigrade scale ), which is in common use throughout most of the world. Water freezes at 0$^{\circ}$ C and boils at 100 °C, and the normal body temperature ( rectal ) is about 37 °C.

Another important temperature scale used for scientific work is the Kelvin (°k ), or absolute, scale, which has the same degree intervals as the celsius scale; °0 K ( absolute zero ) is -273.15 °C. On the absolute scale water freezes at 273.15 °K and boils at 373.15 °K, and the normal body temperature ( rectal ) is about 310 °K ( Fig. 1 ). This temperature scale is not used in medicine.

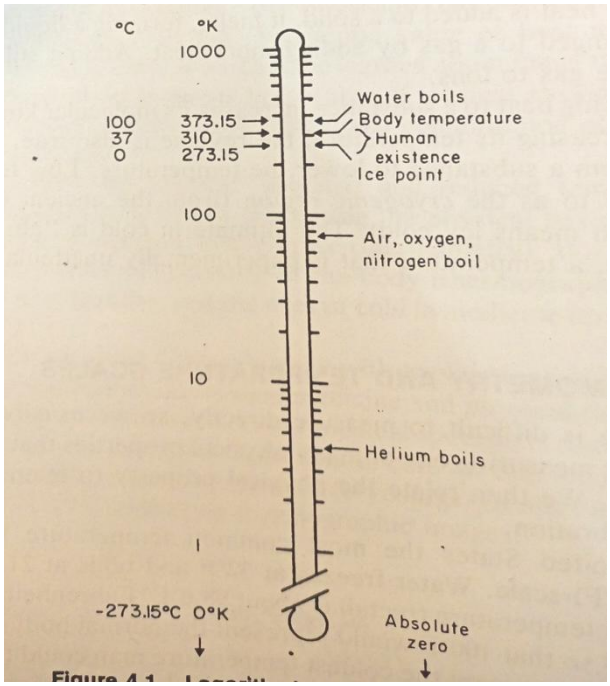



Figure 1

## Thermograph

Figure 2 shows a basic thermographic unit used to measure the radiation emitted from a part of the body. Radiation from a small area of a patient (~ 5 mm in diameter ) is passed by a mirror arrangement through a mechanical chopper to a detector, which is usually cooled to increase its sensitivity. The chopper changes the continuous radiation to an alternating signal so that it can be more easily amplified. The IR transparent filter removes visible light, and the detector converts the IR ( or body heat ) radiation to an electrical signal that proportional to the temperature of the surface from which the radiation originated. In order to give a heat picture of the total surface, a mechanical system moves the mirrors so the heat from different body areas can be detected. The position and magnitude of the radiation from each part of the patient are displayed on the cathode ray tube ( CRT ) of an oscilloscope; the brightness of the image is determined by the temperature, and its position on the screen corresponds to the area of the body being scanned. The CRT displays the different body temperatures as different shades of gray; the hot areas can be shown as either black or white.

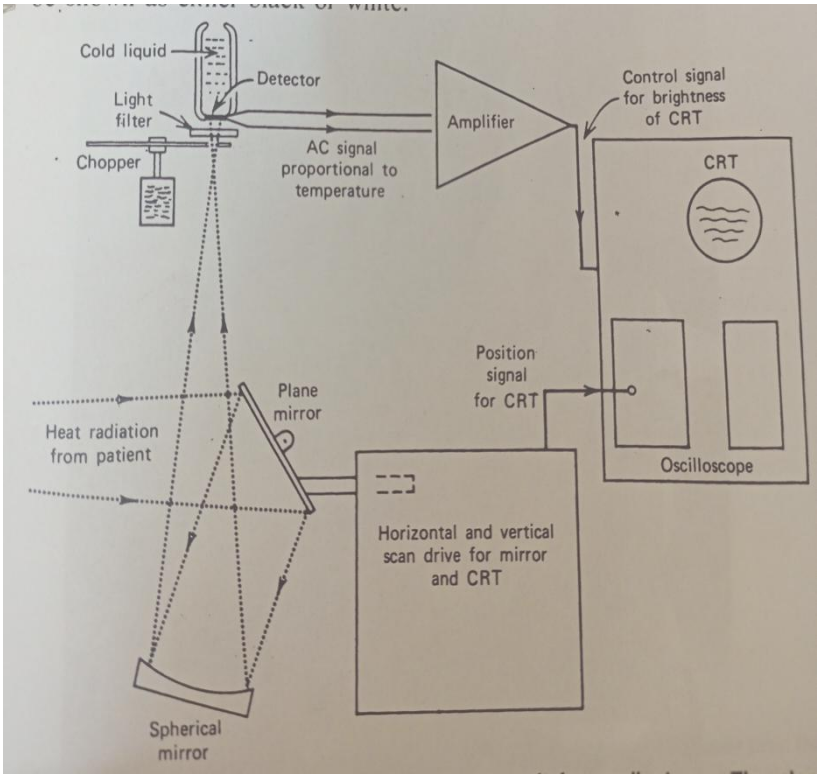



Figure 2

## Cold medicine

Cryogenics is the science and technology of producing and using very low temperatures. The study of low-temperature effects in biology and medicine is called cryobiology.

How are cryogenic method used in medicine? Low temperatures have been used for long-term preservation of blood, sperm, bone marrow, and tissues.

The biochemical and physical processes that sustain life are temperature dependent, lowering the temperature reduces the rates of the processes. Preservation is much better at the temperature of liquid nitrogen ( -196 $^{\circ}$C ) than at the temperature of solid carbon dioxide ( -79 $^{\circ}$C ).

## Cryosurgery

Cryogenic methods are also used to destroy cells; this application is called cryosurgery. Cryosurgery has several advantages:

1. There is little bleeding in the destroyed area.
2. The volume of tissue destroyed can be controlled by the temperature of the cryosurgical probe.
3. There is little pain sensation because low temperatures tend to desensitize the nerves.

### Uses of cryosurgery:

1. In the treatment of Parkinson's disease ( " shaking palsy " ), a disease associated with the basal ganglion of the brain.
2. In the treatment of tumors and warts.
3. In several types of eye surgery.

## Thermal conductivity

The thermal conductivity $K$ describes how the temperature varies ($\Delta T$ ) spatially due to the heat flow between different regions that are separated by a distance $\Delta x$. (Conversely, it also describes how much heat flows due to this spatial variation in temperature.) This relation is

$$\frac{1}{A}\frac{\mathrm{d}Q}{\mathrm{d}t} = -K\frac{\mathrm{d}T}{\mathrm{d}x} \sim -K\frac{\Delta T}{\Delta x} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

The left-hand side is the amount of heat that flows per unit area $A$ per unit time, and is also called the heat flux. The minus sign indicates that heat flows from hotter regions to colder regions. When there is a well-defined distance $d = \Delta x$ between two regions of different but uniform temperature, say due to the thickness of clothing or an air boundary layer, we can define a heat transfer coefficient per unit area $h = K/d$ and then

$$\frac{1}{A}\frac{\mathrm{d}Q}{\mathrm{d}t} = -h\Delta T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Heat flow due to other mechanisms, such as due to radiation, can often be expressed in terms of (1) or (2).

One consequence of thermodynamics is that engines that convert chemical energy to heat and use that heat for mechanical work, so-called heat engines, have a limited efficiency to do such useful mechanical work. An ideal heat engine has a maximum efficiency of $\epsilon = 1 - (T_c/T_h)$ when it operates at a temperature $T_h$ and rejects heat to a lower temperature $T_c$ (both expressed in K). Humans operate internally at about $T_h$= 310K and reject heat to a $T_c \simeq 293$K ambient, so $\epsilon$ would be 5.5% if we were heat engines. This is much less than the ~25% efficiency of humans converting chemical energy into mechanical work. This is not a contradiction because we use the chemical energy directly to do mechanical work and do not produce heat in an intermediate step.

The thermal conductivity of various body tissues is given in Table 1 and that of common materials in Table 2.

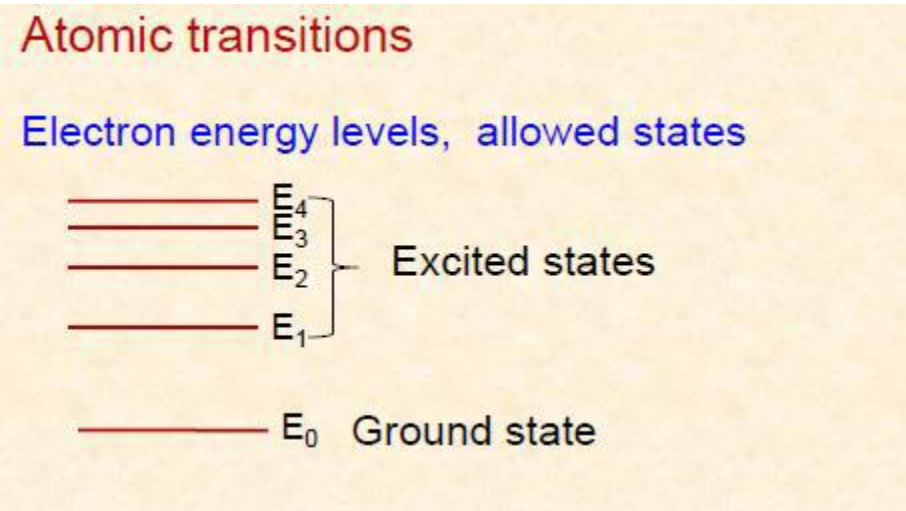
**Table 1.** Thermophysical characteristics of body tissues and organs and other materials.

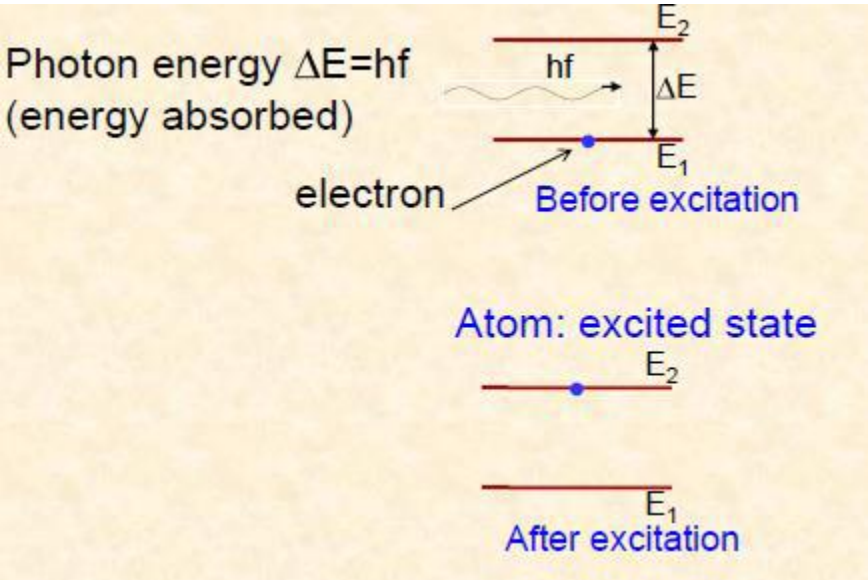
| organ or tissue | thermal conductivity $K$ (W/m-K) | specific heat $c_v$ (MJ/m$^3$-K) | density (approximate) $\rho$ (kg/m$^3$) |
|---|---|---|---|
| skin – very warm | 2.80 | 3.77 | 1,000 |
| skin – normal hand | 0.960 | 3.77 | 1,000 |
| skin – cold | 0.335 | 3.77 | 1,000 |
| subcutaneous pure fat | 0.190 | 1.96 | 850 |
| muscle – living | 0.642 | 3.94 | 1,050 |
| muscle – excised, fresh | 0.545 | 3.64 | 1,050 |
| bone – average | 1.16 | 2.39 | 1,500 |
| bone – compact | 2.28 | 2.70 | 1,790 |
| bone – trabecular | 0.582 | 2.07 | 1,250 |
| blood – water at 310 K | 0.623 | 4.19 | 993 |
| blood – plasma (Hct = 0%) at 310 K | 0.599 | 4.05 | 1,025 |
| blood – whole (Hct = 40%) | 0.549 | 3.82 | 1,050 |
| heart – excised, near fresh | 0.586 | 3.94 | 1,060 |
| liver – excised, near fresh | 0.565 | 3.78 | 1,050 |
| kidney – excised, near fresh | 0.544 | 4.08 | 1,050 |
| abdomen core | 0.544 | 3.89 | 1,050 |
| brain – excised, near fresh | 0.528 | 3.86 | 1,050 |
| brain – living | 0.805 | – | – |
| lung – excised, bovine | 0.282 | 2.24 | 603 |
| whole body (average) | – | 4.12 | 1,156 |

**Table 2.** Thermophysical characteristics of materials.

| material | thermal conductivity $K$ (W/m-K) | specific heat $c_v$ (MJ/m$^3$-K) | density $\rho$ (kg/m$^3$) |
|---|---|---|---|
| air | 0.009246 | 0.00119 | 1.18 |
| cotton fabric at 310 K | 0.0796 | 0.0267 | 160 |
| rubber | 0.156 | 2.41 | 1,200 |
| ethanol at 310 K | 0.163 | 1.96 | 789 |
| teflon | 0.399 | 2.20 | 2,180 |
| concrete | 0.934 | 1.93 | 2,310 |
| glass, plate | 1.09 | 1.94 | 2,520 |
| ice at 249 K (−42°C) | 2.21 | 1.76 | 913 |
| sapphire (normal to $c$-axis) at 310 K | 2–20 | 2.89 | 3,970 |
| stainless steel | 13.8 | 3.68 | 7,910 |
| aluminum | 204 | 2.45 | 2,710 |
| silver | 405 | 2.59 | 10,500 |
| diamond, natural | 2,000 | 1.82 | 3,510 |

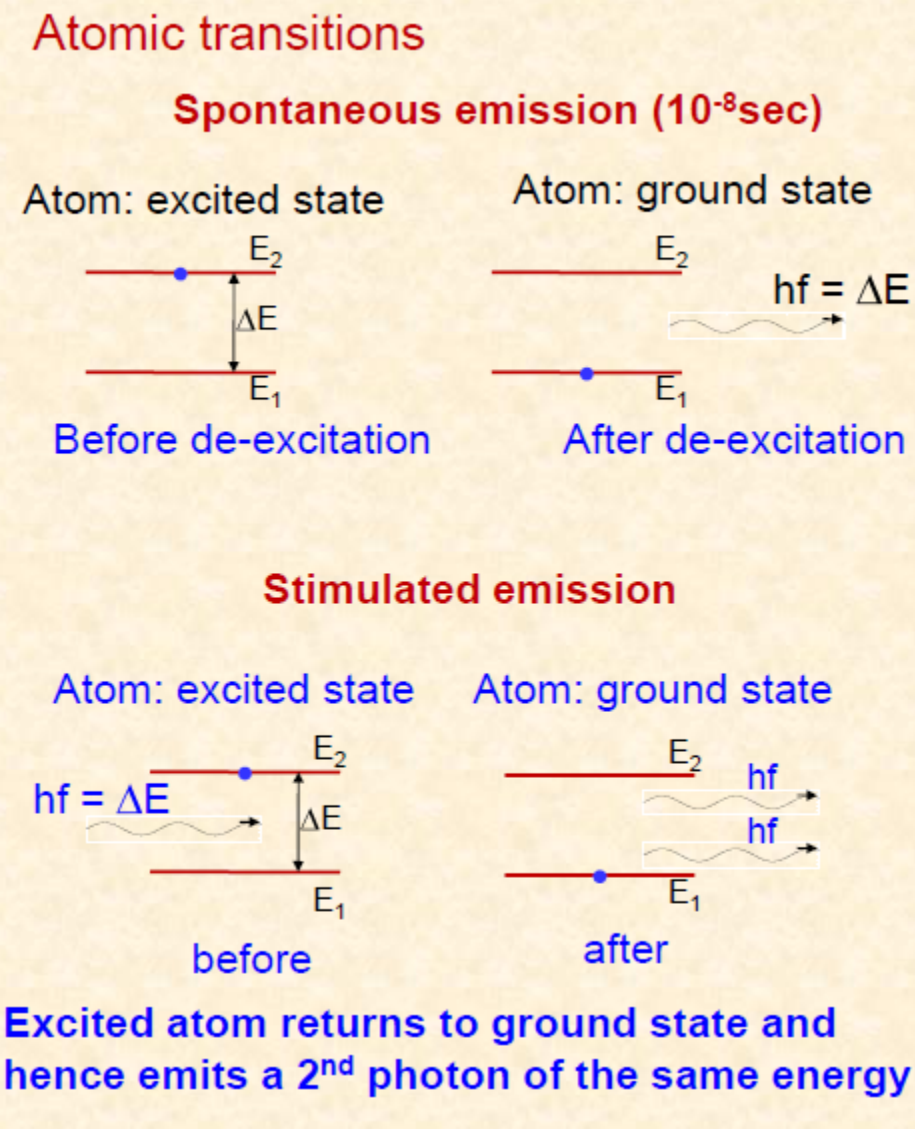
# Laser in medicine



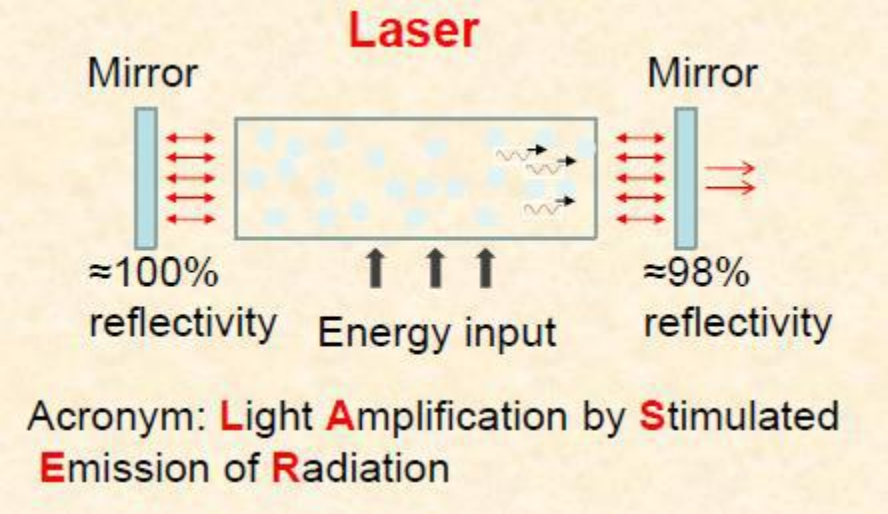
## Population inversion

Ordinarily more atoms in the ground state than excited state population inversion happens if there are more atoms in the excited state than the ground state




Both photons are in phase and have the same energy (color) (wavelength)

Both photons can stimulate other atoms to emit photons that in turn stimulate the emission of more photons.



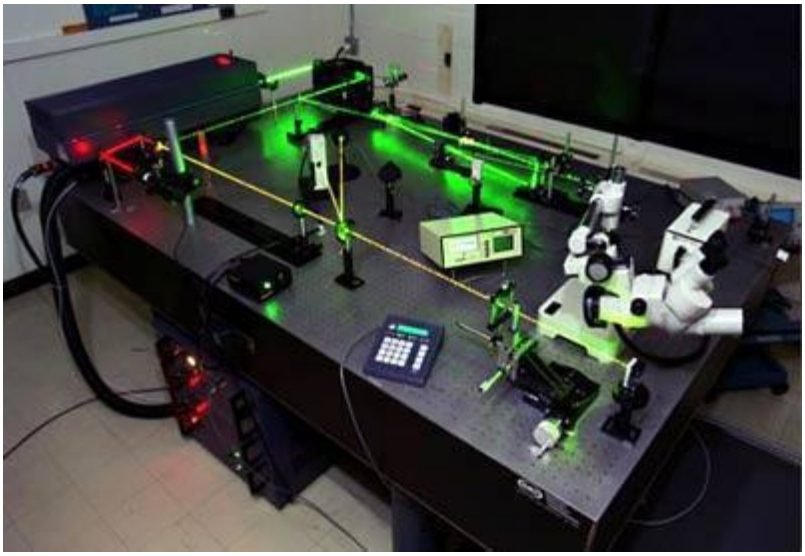

## Laser Typical Characteristics

•uni-directional; same direction

•Single wavelength in visible region; same frequency

•same phase

•Intense beam



## General Applications

•CD players

•Pointers

•Printers

•Eye surgery (reshaping cornea)

•Cuts tissue (burns tumours)

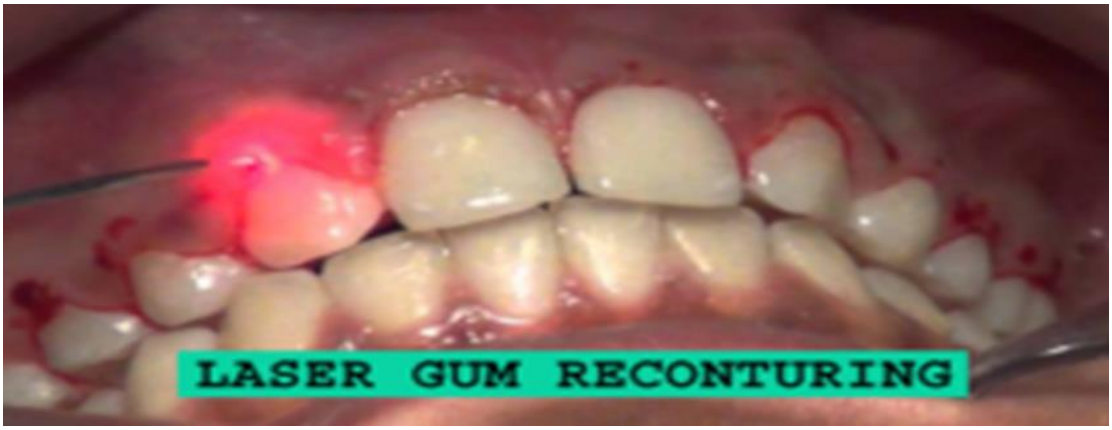
•Cuts metal

•Cuts patterns (many layers of cloth at once)

•Telecommunications (sent down optical fibers)

## Laser Dental Applications

1- Reshape gum tissue (reduce prominence)




2- Laser aided teeth whitening

3. Laser Drill

•Capable of killing bacteria located in a cavity

•No vibration

Laser: Erbium Yag (Er: YAG) Wavelength 2940 nm, light of this wavelength highly absorbed by water

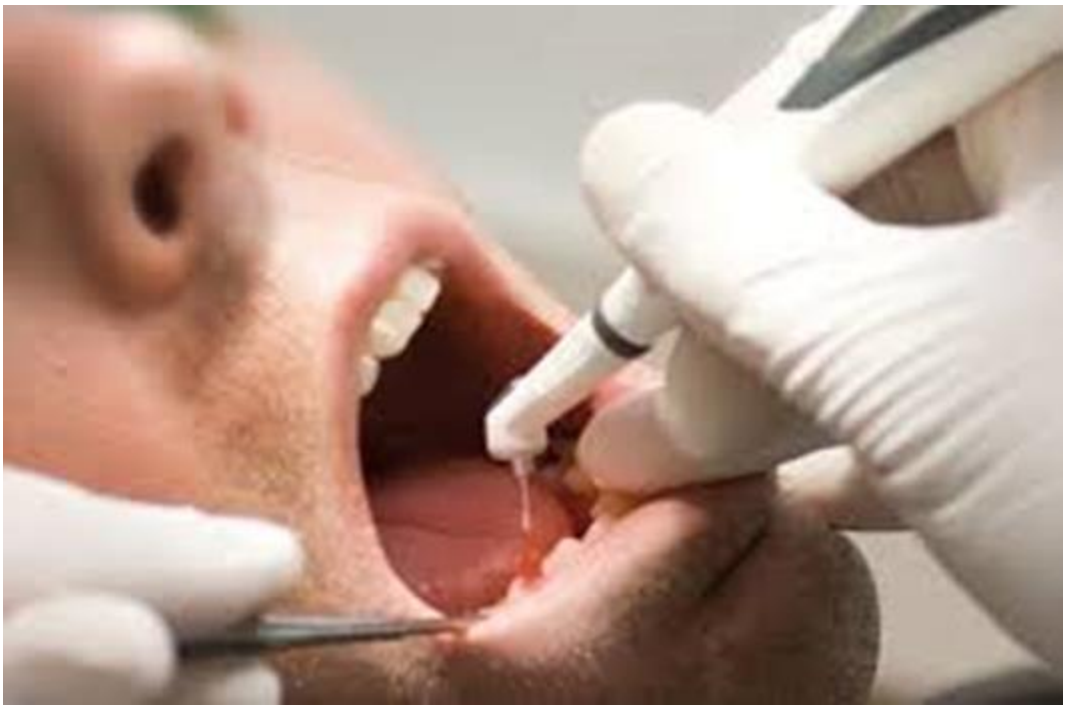
Laser beam absorbed by decayed tissue because of large water content compared with healthy enamel

Result:

•selective ablation of decay,

•conservation of healthy tooth

•no increase in pulp temperature



# Light in medicine

## Properties of light

Light has some interesting properties, many of which are used in medicine:

1. The speed of light changes when it goes from one material into another. The ratio of the speed of light in a vacuum to its speed in a given material is called the index of refraction. If a light beam meets a new material at an angle other than perpendicular, it bends, or is refracted. This property permits light to be focused and is the reason we can read and see objects clearly.
2. Light behaves both as a wave and as a particle. As a wave it produces interference and diffraction, which are of minor importance in medicine. As a particle it can be absorbed by a single molecule. When a light photon is absorbed its energy is used in various ways. It can cause a chemical change in the molecule that in turn can cause an electrical change. This is basically what happens when a light photon is absorbed in one of the sensitive cells of the retina (the light-sensitive part of the eye). The chemical change in a particular point of the retina triggers an electrical signal to the brain to inform it that a light photon has been absorbed at that point.
3. When light is absorbed, its energy generally appears as heat. This property is the basis for the use in medicine of IR light to heat tissues. Also, the heat produced by laser beams is used to "Weldon" detached retina to the back of the eyeball and to coagulate small blood vessels in the retina.
4. Sometimes when a light photon is absorbed, a lower energy light photon is emitted. This property is known as fluorescence; as you may guess, it is the basis of the fluorescent light bulb. Certain materials fluoresce in the presence of UV light, sometimes called "black light" and give off visible light. The amount of fluorescence and the color of the emitted light depend on the wavelength of the UV light and on the chemical composition of the material that is fluorescing. One may fluorescence is used in medicine is in the detection of porphyria, a condition in which the teeth fluoresce red when irradiated with UV light.
5. Light is reflected to some extent from all surfaces. There are two types of reflection (Fig. 1 ). Diffuse reflection occurs when rough surfaces scatter the light in many direction. Specular reflection is a more useful type of reflection; it is obtained from very smooth shiny surface such as mirrors where the light is reflected at an angle that is equal to the angle at which it strikes the surface. Mirrors are used in many medical

instruments. One simple instrument is a mirror that is held at the back of a patient's throat to look at his vocal folds.

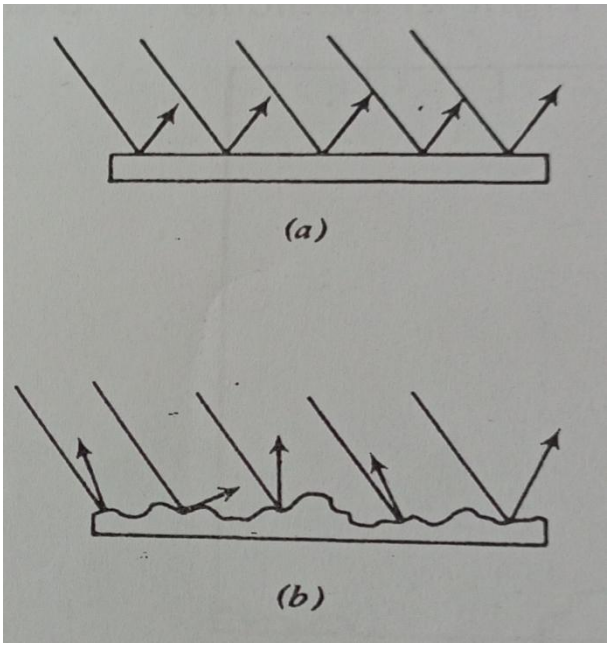



Figure 1

## Measurement of light and its units

The three general categories of light-UV, visible, and IR-are defined in terms of their wavelengths. Wavelengths of light used to be measured in microns ($1\mu=10^{-6}$ m) or in angstroms ($1\ ^{\circ}A=10^{-10}$ m), but at present the recommended unit is the nanometer ($1\ nm=10^{-9}$ m). Ultraviolet light has wavelengths from about 100 – 400 nm; visible light extends from about 400-700 nm; and IR light extends from about 700 to over $10^4$ nm. Each of these categories is further subdivided according to wavelength ($\lambda$). For example, UV-C has wavelengths from about 100 to 290 nm, UV-B has wavelengths from 290 to 320 nm, and UV-A has wavelengths from 320 -400 nm.

Visible light is measured in photometric units. All light radiation, including UV and IR radiation, can be measured in radiometric units.

Light is a form of energy, it is sometimes useful to talk about the energy of individual light photons. Figure 2 gives the energies as well as the wavelengths of the different parts of the electromagnetic spectrum.

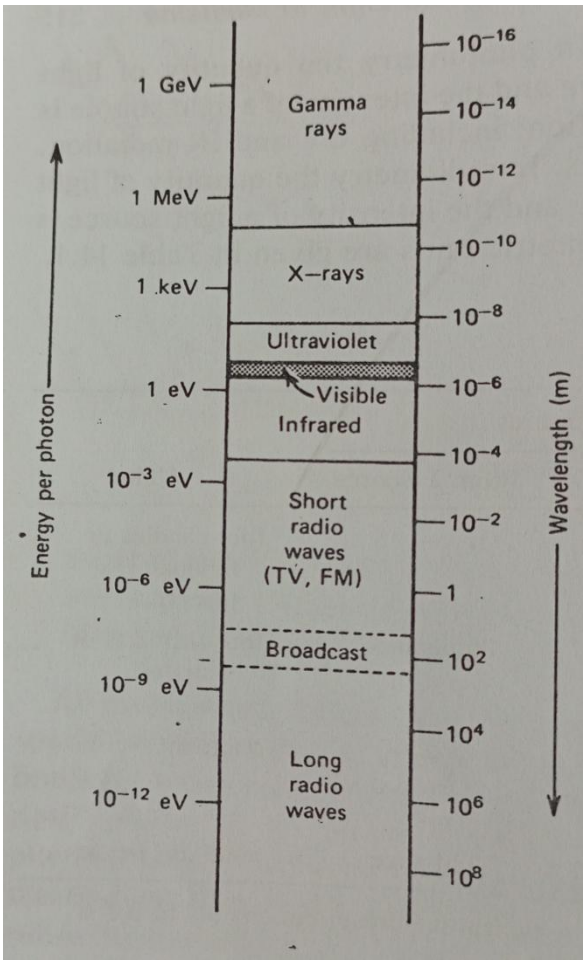



Figure 2

**Applications of visible light in medicine**

An obvious use of visible light in medicine is to permit the physician to obtain visual information about the patient regarding, for example, the color of his skin and the presence of abnormal structures in or on his body.

A number of instruments, called endoscope, are used for viewing internal body cavities. Special purpose endoscope are often given names indicating their purpose. For example, cystoscopes are used to examine the bladder, proctoscopes are used for examining the rectum, the bronchoscope are used for examining the air passages into the lungs.

Transillumination is the transmission of light through the tissue of the body and its used :

1. In the detection of hydrocephalus (water-head) in infants.
2. To detect pneumothorax (collapsed lung) in infants.

Visible light has an important therapeutic use. Since light is a form of energy and is selectively absorbed in certain molecules, it should not be surprising that it can cause important physiological effects. Many premature infants have jaundice, a condition in which an excess of bilirubin is excreted by the liver into the blood. Relatively recently (1958) it was discovered that most premature infants recover from jaundice if their bodies are exposed to visible light (phototherapy). The exact mechanism is not clear, but blue light ( ~450 nm) appears to be the most important component.

## Applications of ultraviolet and infrared light in medicine

The wavelengths adjacent to the visible spectrum also have important uses in medicine. Ultraviolet photons have energies greater than visible photons, while IR photons have lower energies. Because of their higher energies, UV photons are more useful than IR photons.

Ultraviolet light with wavelengths below about 290 nm is germicidal that is, it can kill germs and it is sometimes used to sterilize medical instruments. Ultraviolet light also produces more reactions in the skin than visible light. Some of these reaction are beneficial, and some are harmful.

Ultraviolet light from the sun affects the melanin in the skin to cause tanning. However, UV light can produce sunburn as well as tan the skin. The wavelengths that produce sunburn are around 300 nm, just at the edge of the solar spectrum (Fig. 3).

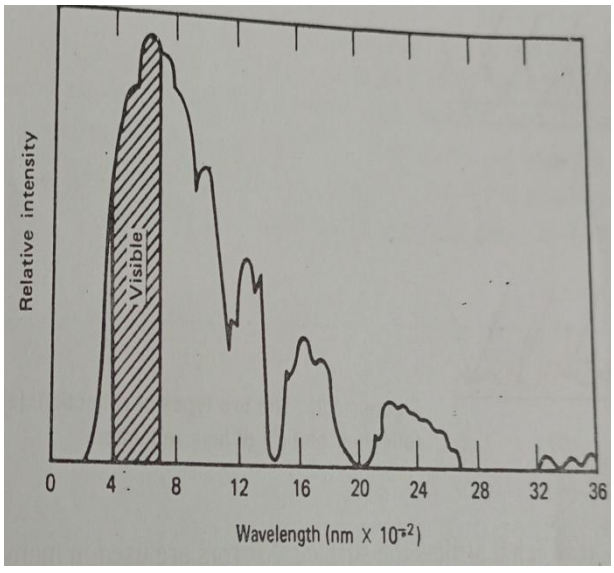



Figure 3

Solar UV light is also the major cause of skin cancer in humans. The UV wavelengths that produce sunburn are also very well absorbed by the DNA in the cells.

The large percentage of near-UV light absorbed by the lens may be the cause of some cataracts (opacities of the lens).

About half of the energy from the sun is in the IR region (Fig. 3). The IR rays are not usually hazardous even though they are focused by the cornea and lens of the eye onto the retina. The IR wavelengths can cause a burn on the retina.

Heat lamps that produce a large percentage of IR light with wavelengths of 1000-2000 nm are often used for physical therapy purposes. Infrared light penetrates further into the tissues than visible light and thus is better able to heat deep tissues.

Two types of IR photography are used in medicine: reflective IR photography and emissive IR photography. The latter, which uses the long IR heat waves emitted by the body that give an indication of the body temperature, is usually called thermography. Here reflective IR photography, which uses wavelengths of 700-900 nm to show the patterns of veins just below the skin. Some of these veins are visible to the eye, but many more can be seen on a near-IR photograph of the skin.

# X-Ray

**X-Ray is an electromagnetic waves the same as light, radio waves, microwaves, ultraviolet and ɣ-ray.**

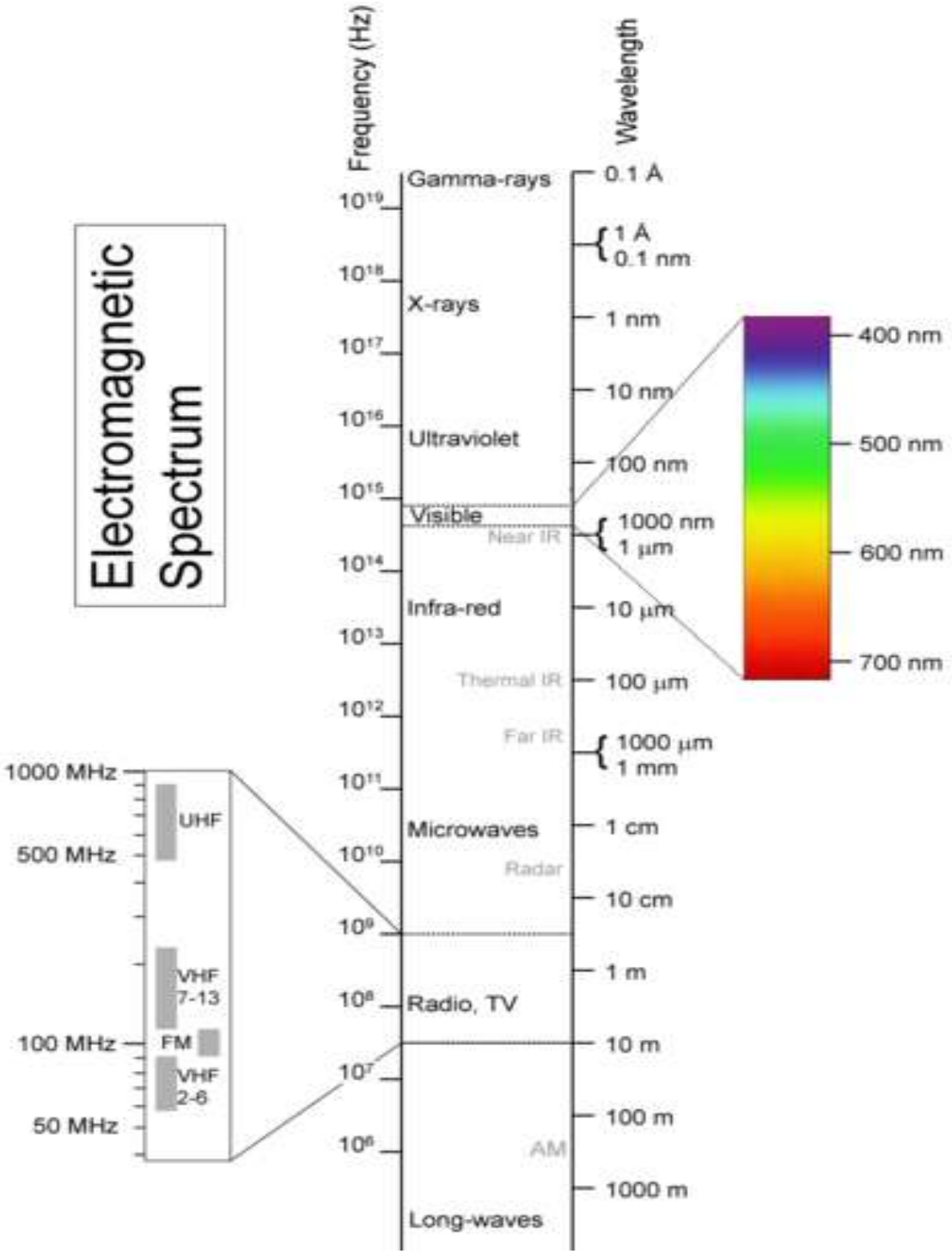
**These electromagnetic waves are different by their energy for example ultraviolet has higher energy than visible light and infrared, ɣ-ray has higher energy than UV.**

**X-ray is a high electromagnetic wave has higher energy than all electromagnetic waves except for ɣ-ray which has energy in the region of X-ray, the higher energy electromagnetic waves obviously has higher frequency and short wave length.**

**In quantum physics these electromagnetic waves called photons (bundles or packs of energy) each pack of energy in one photon.**

**ʘ so the X-ray is high energy electromagnetic waves or high energy photons.**

**This higher energy photons i.e. X-ray has higher penetration power through materials and this property is proportional with its energy (The higher energy is the higher penetration power).**


Electromagnetic Spectrum
Frequency (Hz)
Wavelength
Gamma-rays
X-rays
Ultraviolet
Visible
Near IR
Infra-red
Thermal IR
Far IR
Microwaves
Radar
Radio, TV
AM
Long-waves
0.1 A
1 A
0.1 nm
1 nm
10 nm
100 nm
1000 nm
1 μm
10 μm
100 μm
1000 μm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1000 m
400 nm
500 nm
600 nm
700 nm
1000 MHz
500 MHz
100 MHz
50 MHz
UHF
VHF 7-13
FM
VHF 2-6

## X-ray production:

**When fast electrons (with high energy) are brought to rest suddenly these electrons will give their kinetic energy as electromagnetic waves.**

**These electromagnetic waves can be of different nature depending on their energy i.e. it can be heat (infrared), UV or X-rays.**

**The production of X-ray is based on this principle so, they have the following properties:**

**A- Accelerated electrons.**
**B- A target which can stop these electrons abruptly.**

**To satisfy these conditions the following was done:**

**1-Electron emitter, a filament which emits electrons by heat.**

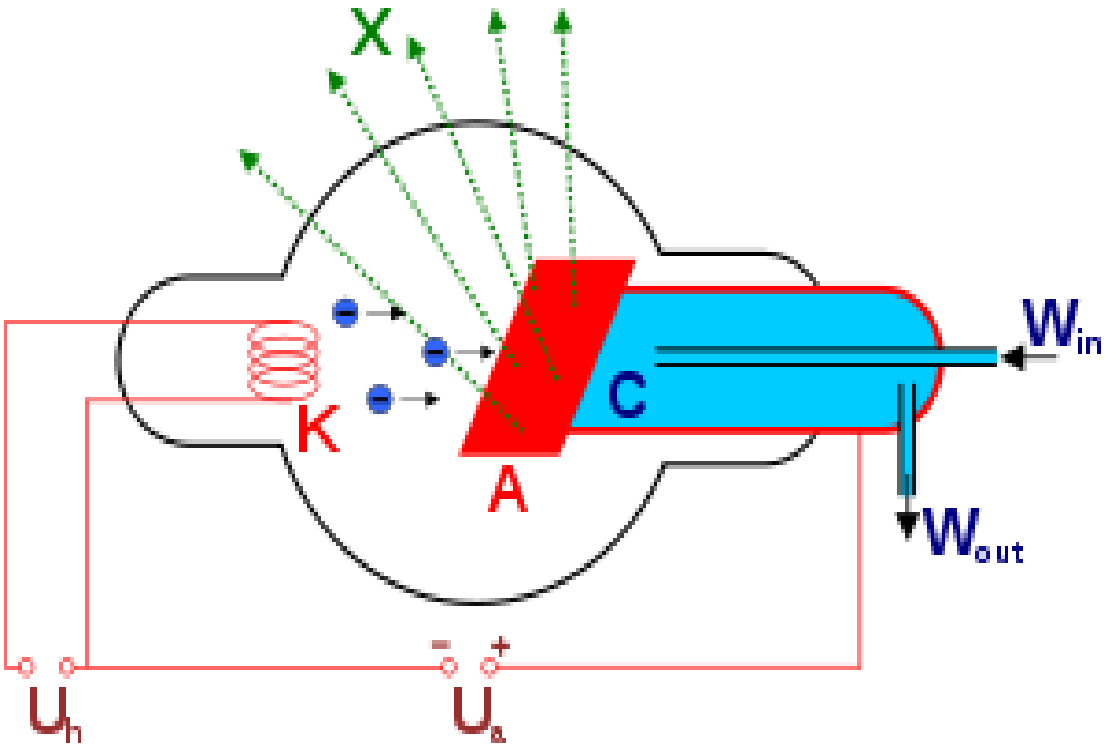
**2-The target is to stop the fast electrons suddenly.**

**3-High voltage is between the filament and target (cathode and anode) to accelerate the electrons to high speed.**

**4-the target and the filament are kept in vacuum to allow the accelerated electrons to move freely not to be obstructed by air atoms.**

**Having done all the above points we can produce X-ray by:**

- **Heating the filament will emit electrons(thermo-ionic emission )**
- **These electrons is accelerated to a very fast speed by keeping the potential between the target and the filament (anode and cathode)very high of order of hundred thousand of volts, then**
- **These electrons will strike the target and**
- **Give it energy as an electromagnetic energy, which gives the X-ray spectrum.**




**►►In the diagnostic range of X-ray, the tube voltage is in general between 20----100KV.**

**99% of the electron energy goes to heat and 1% is converted to X-ray emission which is called bremsstrahlung and sometimes is called the white radiation, which is not common name, as it is a continue spectrum similar to white light spectrum.**

**The choice of target should be of high melting point and high efficiency to produce X-ray for this reason tungsten chosen because:**

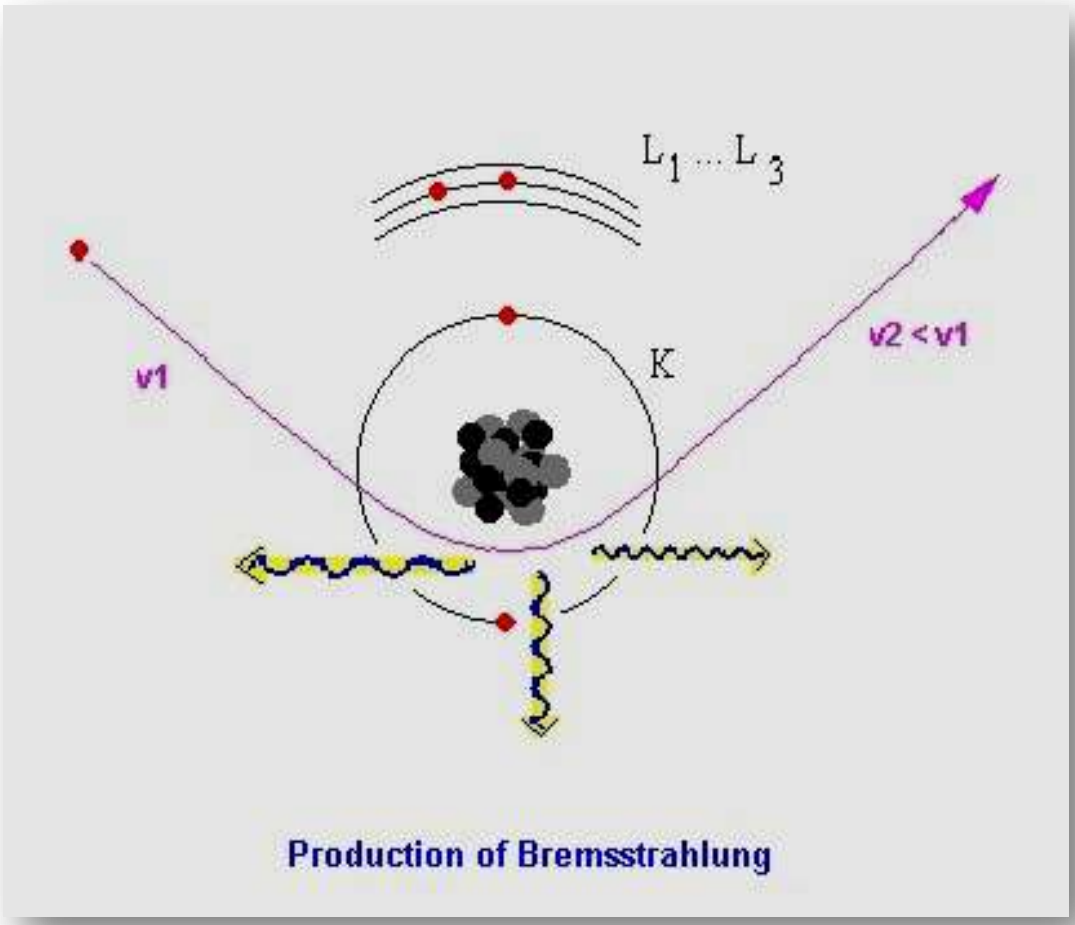
1) **It has high atomic number and**
2) **High melting point.**

**The continue spectrum formed when the fast electrons strike the target they do not stop at once they will make several interactions in each interaction the incident electron will:**

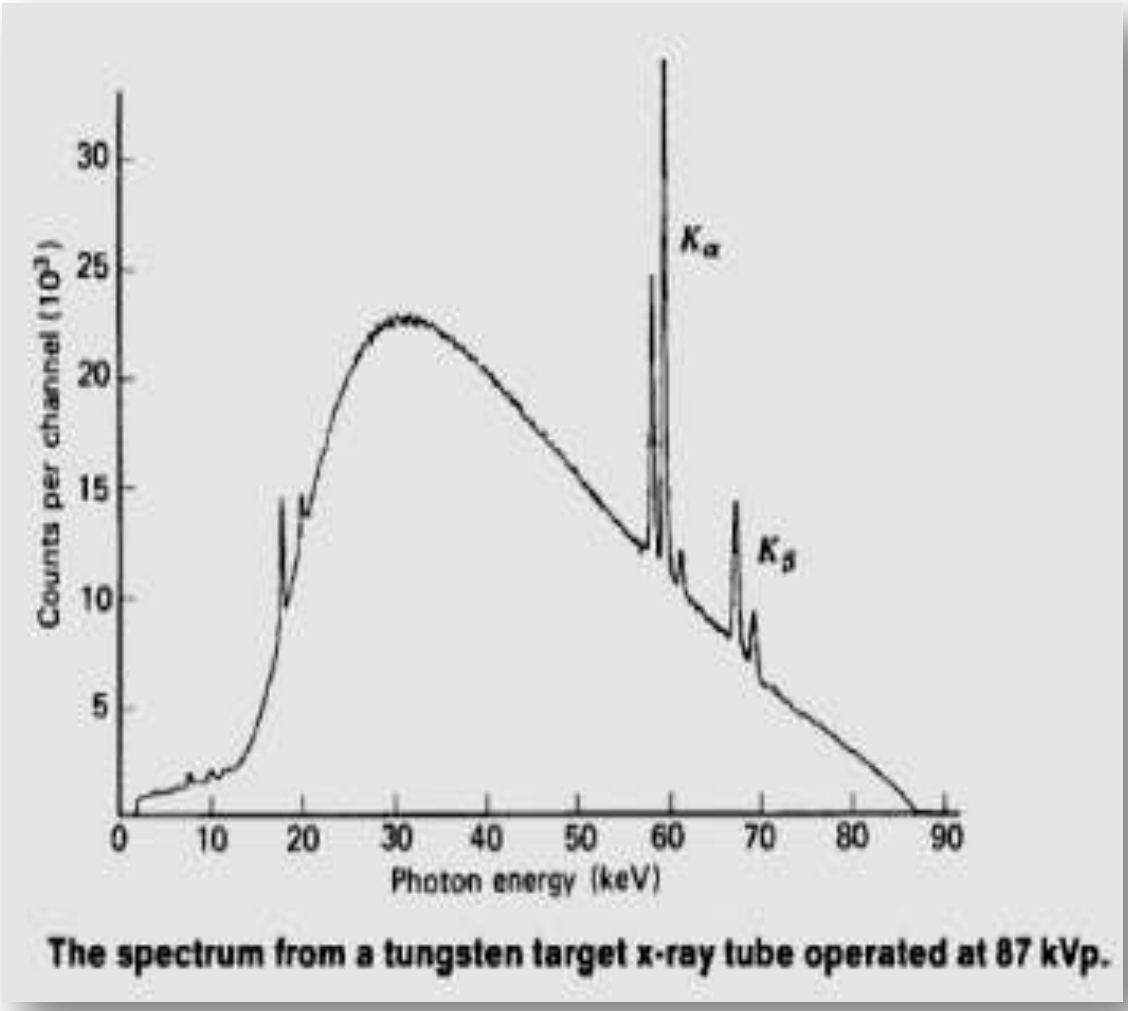
► **lose energy by energy and**

► **will change direction inside target.**

**These types of interactions are electrostatic type of interactions between the fast electrons and the target atom either with electron or field of the nucleus (fig 16.7).**




**In each interaction there is an energy loss then there will be photon emission equivalent to the same loss of kinetic energy. For this reason the X-ray will be produced in wide range of energy called the X-ray spectrum of (the continuous spectrum) fig16.7, p.394**




**The spectrum from a tungsten target x-ray tube operated at 87 kVp.**

## Characteristic X-ray:

**As the fast electrons strike the target a part of the electron energy will be absorber within the target atoms. This energy will cause excitation and ionization in the target atoms. Electrons from the inner shells of the atoms such as L – shell or K – shell may either**

**shifted to a higher energy level causing excitation or leaves the atom causing in this case ionization.**

**When another electron fails immediately from the upper energy level such as M or L shell to fill the vacancy, it will give energy in the form of electromagnetic waves (photons) if these in the range of X –ray energy it will show as an X –ray and it is called the characteristic X –ray which can be seen as lines in the X- ray spectrum so this type of X-ray are from the target atoms, and it is a characteristic of the type of material from which the target is made and it's named (characteristic X-ray)( Fig16.8) p.394**

**If the electrons falls from L shell to k shell it will emit Kα characteristic X-ray and if it fall from M level to K it will be Kβ characteristic X-ray.**

**►The elimination of heat energy produced during X-ray machine operation:**

**The high amount of heat energy produced during X-ray machine operation 99% of the fast electrons energy can limit the X-ray tube exposure time, the size of the focal spot, KV and the tube current, because all these factors can increase the quantity of heat produced.**

**The increase in the target temperature can damage the target or even melt the target for this reason several**

**methods have been designed to eliminate this heat such as:**

## 1-The rotating target:

**In this design the target is made to rotate during the X-ray exposure in downing so the focal spot will be distributed around circumference large area of the conference of the target meaning that instead of the electrons strike the target on area, for example 1 $mm^2$ it will strike it an area of 1 $mm^2$ times the circumference of the target in this way the heat can be distributed among large area which reduce the local heating on the target.**

**The rotating speed of the target is 3600 rpm or sometimes goes up to $10^4$ rpm for very short exposure.**

**This high speed is to make the electrons strike the target on area of one revolution at least.**

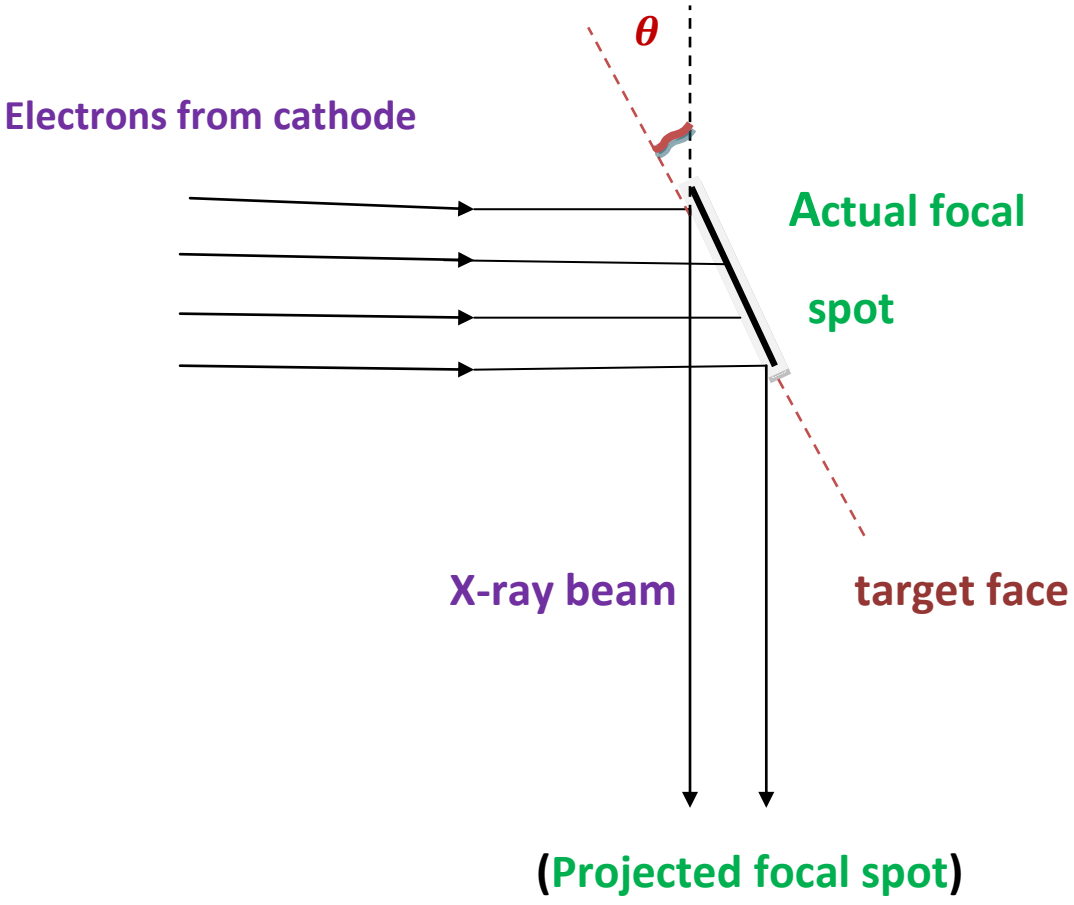
**The high speed heavy target should be balanced very well if it not, it will shatter the tube even a slight imbalance may cause resonance with the natural frequency of the target often the X-ray is being stopped. For this reason the target is not left to stop freely but it is broken rapidly.**

## 2-Target material:

**The X-ray production is more efficient when electrons strike high atomic number materials because it has high charge in her nucleus and high number of electrons.**

**►So the accelerated fast electron will be stopped more efficient by the electrostatic interaction with the target atom. And because of that the X-ray production liberates high quantity heat.**

## 3-Focal spot size (line focal spot):



**The angle between target and x-ray beam is $10^0$-$20^0$, the projected focal spot is smaller than the area struck by electrons (large area struck by electron increases the distributed heat over large area)**

**The decreasing size of focal spot can introduce a better image.**

## $X-ray\ absorption$:

**When X-ray penetrates through matter part of the X-ray beam will be absorbed and scattered.**

**The mod of absorption is given in the following equation:**

$$\mathrm{I} = Io\ e^{-\mu\chi}$$

$I$ **is the emerging beam intensity**

$Io$ **is the original beam intensity**

$\mu$ **is the attenuation coefficient**

$\chi$ **is the thickness of the absorber**

## Photo electric effect:

**This type of interaction is happened when the electron of the absorber atoms absorbs all the energy.**

**This energy will be consumed in Ripping taking off the electron from the atom in another word to overcome the binding energy of the electron with the nucleus of the atom.**

**The other part of the energy will be taken by the electron as kinetic energy.**

$$h\,f = W + \frac{1}{2}\ m\,v^2$$

$h\,f$ **is the X-ray photon energy**

$w$ **is the binding energy of the absorber atoms?**

$\frac{1}{2}\ mv^2$ **is the kinetic energy of the electron**

- **Photoelectric effect α (1/hf)$^3$ and α z3**

**h plank' constant**

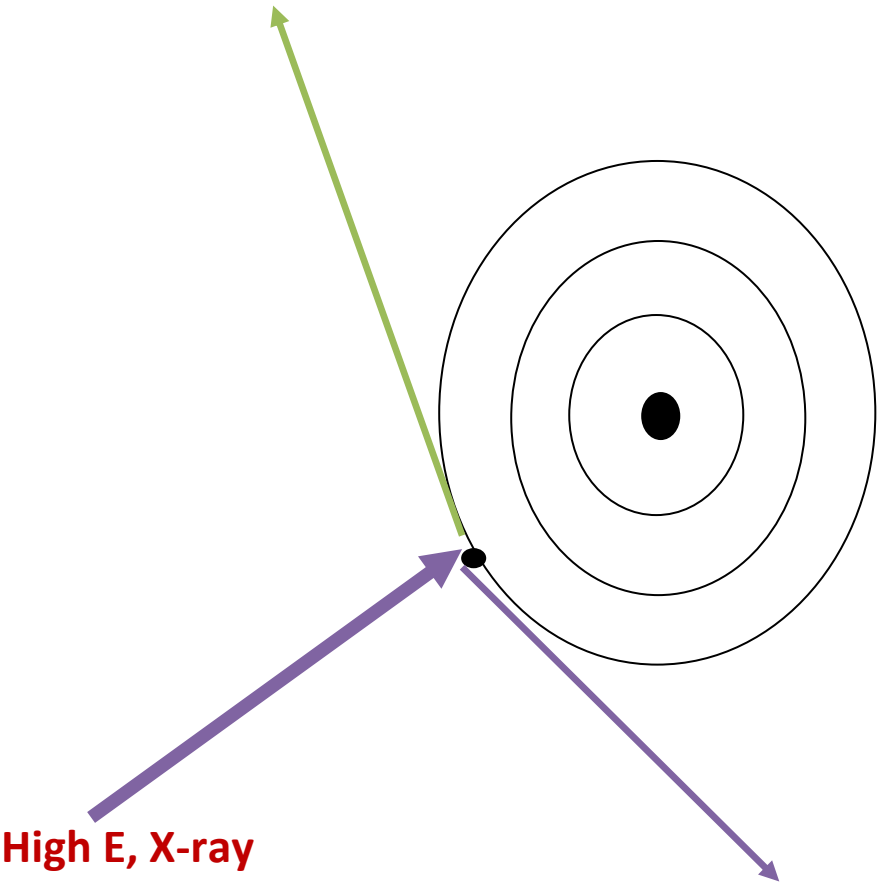
**f x-ray frequency**

**z absorber atomic number**

## Compton effect:

**This type of interaction involves the interaction of X-ray photons with free electrons or electrons with very week binding energy these are found at the outer shells of the absorber atoms. In this interaction the photon strikes the free electron, give part of its energy to the electrons and the photon will scatter with less energy, (less frequency and longer wave length) in a different direction, the most probable interaction will be at photon energy equivalent to mass energy of the electron 0.51 Mev (if we change the mass of electron to energy it will give 0.51 Mev).**

Recoil electron



High E, X-ray

Energy

low energy of x-ray

►**This interaction depends mainly on the number of electrons per gm electron density.**

## Pair production:

**This is the third type of interaction occurs when a high energy photon interacts with strong electric field of nucleus it will disappear and form a pair of particles (electrons $e^-$ , positron $e^+$) it has a threshold value of 1.02 Mev equivalent to mass energy of both electron and positron (0.51+0.51) =1.02 Mev this type of interaction is proportional with Z. As Z increases, the atomic electric field of the nucleus increase and the pair interaction increase.**

**When X-ray energy is > 1.02 the extra energy will appear as kinetic energy for the created electron and the positron. The positron live for a very short time soon after being created, it will meet an is electron and annihilation because the positron is the antimatter for the electron and emits radiation called annihilations radiation, sieving photon energy of 1.02 Mev which is a characteristic energy for pair production.**

**In general, the diagnostic range of X-ray pair production is absent because most X-ray energy range approximately in the region of 20-100Kv and in very special techniques and very seldom it will go up to 350Kv .So in diagnostic X-ray the photoelectric effect PE and Compton scatter CS are involved in the X-ray absorption.**

►In the lower Kv (energy) the involvement of PE increases and at a higher Kv CS involvement is increased (fig 16.14) p.400.

►In soft tissue, the contribution of CS is higher than PE because of low atomic number.

►In bone of higher average atomic number it will save absorption for higher PE contribution than the contribution of CS affect.

As a result the linear attenuation coefficient μ is the combination of all interactions:

$$\mu = \mu_{Pe} + \mu_{ce} + \mu_{pp}$$

To eliminate the density effect from the linear absorption coefficient we divided over the density μ/ρ and this is called the mass attenuation coefficient and the units: μ in $cm^{-1}$ ,ρ in g $cm^{-3}$.

$$\mu/\rho = cm^{-1}/g\ cm^{-3} = cm^2/g$$

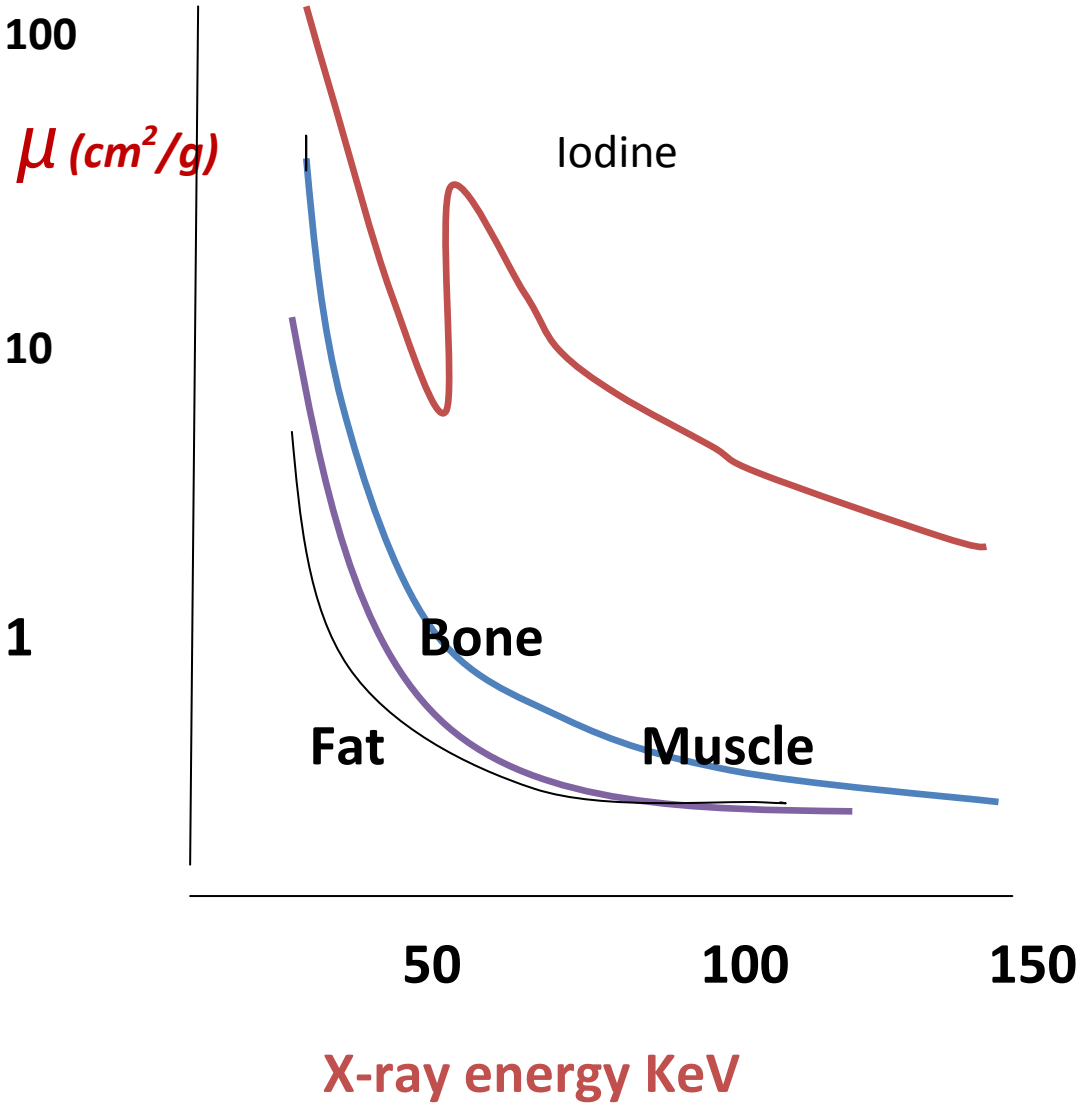
$$\rho\ x = (g/cm^3)\ cm = g/cm^2$$

## K - Absorption edge

When x-ray are absorbed in atoms all electronic shell energies of X-ray energy are involved in absorption, if the X-ray energy are involved in absorption, if the x-ray

**energy is > the binding energy of all energy levels but not the K level the x-ray photons will not be absorbed efficiently.**

**When x-ray energy increased and becomes ≥ the binding energy of K shell, k shell will also contribute in the absorption and because the binding energy of K shell is much higher than all other shells a jump in absorption coefficient occur and can be seen on the graph plotted μ against the x-ray energy fig.16.12,pag.398.**



## X-ray beam filtration:

**As the X-ray beam contains different energies the low energy is not useful on producing a radiograph it will be absorbed within the patient without reaching the *film*.**

**So filters are added into the beam and the choice of filter is to absorb the low energy of X-ray more than higher energy fig 16.28, pag.419,So the filtered beam will be harder ,contains more high energy than low energy photons.**

**By elimination the low energy photons less x-ray will be absorbed in the patient, in other word less dose to the patient.**

## Image improvement:

**A-To increase the image sharpness by:**

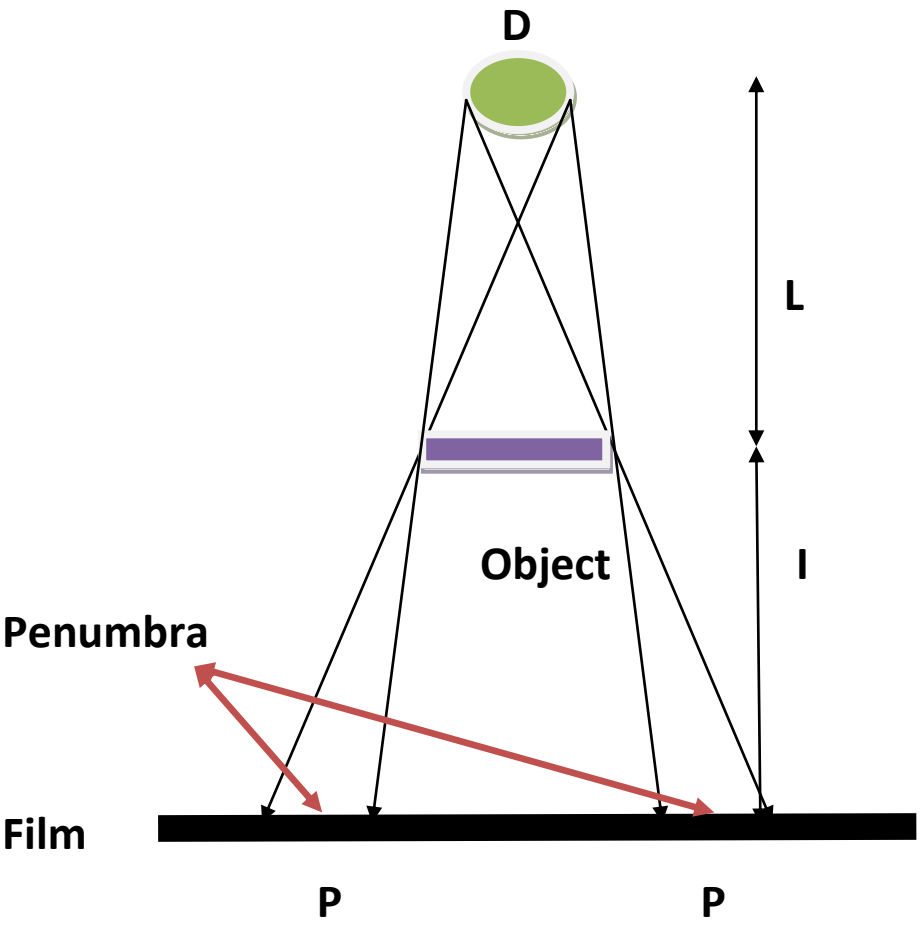
**1-Reduce the focal spot size by angulations of the target between 10°-20° called line focus principal.**

**In this way the effective size of the focal spot will be less than the actual one.fig 16.4,319.**

**2-Using the small focal spot filament this will reduce the focal spot size by reducing the size of electron beam striking the target. The effect of the focal spot**

**size in forming penumbra (p) is shown in fig 16.2, pag.410**

**From the fig.** $$P = \frac{D}{L} x I$$



**B -contrast improvement**

**The scattered radiation can be very destructive to the x-ray image. It is mainly reduce the contrast.**

**To eliminate the scattered radiation:**

**►Reduce the beam size:**

**The beam size should not be unnecessary large because it will increase the scattered radiation and the patient dose, for this reason, light diaphragm is used which can show the x-ray area before exposure.**

**►The use of compression can reduce the tissue volume which in turn reduces the amount of scatter radiation.**

**►The use of the grids: a device composed of lead strips held by plastic strips. The strips are aligned so that the primary beam of x-ray from the source will go through the plastic strips and strike the film while most of the scattered radiation will strike the lead strips and be absorbed.fig 16.23, pag413.**

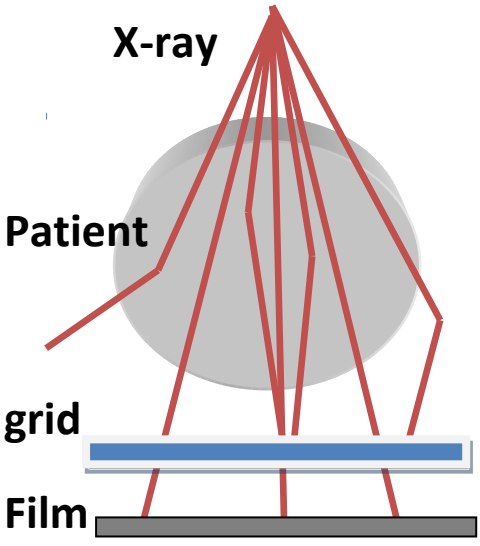
**Because the grid lines might show the radiograph and disturbs the radiograph image a thinner strips were made which cannot be noticed on the radiograph it can reach 4 grids per mm.**

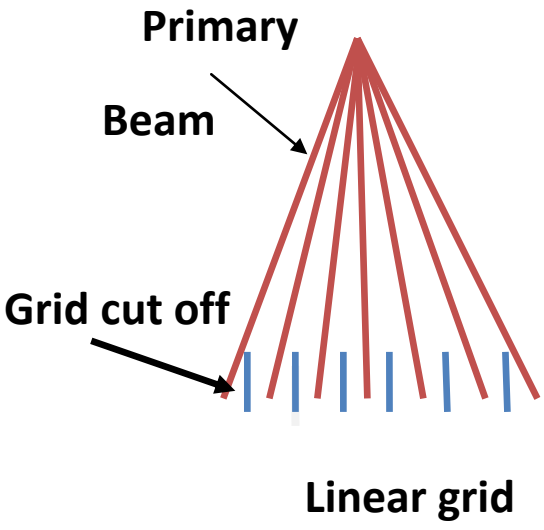
**Other procedures have also been employed to blur the grid lines such as the moving grids, this type the grids**

move fast during the exposure and the grids lines blurred.

Another type of the grid is the focused grid in which the grid lines are angulated towards the beam direction (fig 16.23, Peg. 413) to prevent the grid cut off which occur in the linear grid. As the grid lines will prevent part of the primary beam, not scattered, the tube exposure should be increased when grid is used.

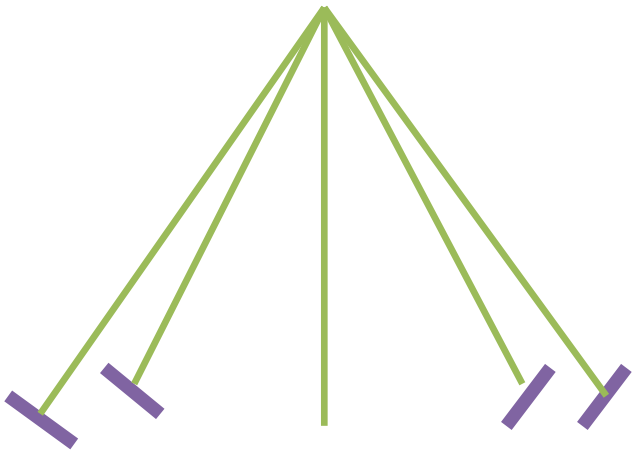
The grid radiograph in some cases is much clear than a radiograph taken without using grid.




In focused grid, it is designed for a certain tube film distance if the grid is inverted it will absorb all x-ray

radiation leaving only the central region from which radiation can reach the film.



Inverted focused grid

# Definitions:

**1-Film density D: It is represented the extent of film darkness after x-ray exposure D=log ($I_o$/I) where $I_o$ is the original light intensity and I is the light after passing through the film, example if $I_o$ =1000 units and I =10 units then D=log 1000/10=log 100=2.**

**2-Contrast: it is the difference in the film density between two adjacent points on the film, example two**

**adjacent points of density of 1 and 2 respectively the contrast C =$D_2$– $D_1$ =2 – 1 = 1.**

**3-Film speed: film speed is the inverse of the amount of the exposure in roentgens R needed to darkened the film so that it transmit only 10% of the incident light ,optical density =1, that is if o.1 R is needed ,the speed is 10 $R^{-1}$.**

**3-Film latitude: it is the range of the exposure in Roentgens which can be given to a film and yet have an acceptable density values.**

## X-ray shadow and contrast media:-

**According to the x-ray interaction with matter we have two types involved in diagnostic radiology there are the photoelectric effect and Compton Effect, the third is pair production which is not involved because it**

**happens at energies much higher than the diagnostic range.**

**As has been mentioned earlier that photoelectric effect is proportional with atomic №. $Z^3$ and is inversely proportional with photon energy (1/ (ht) $^3$). This means that at low energy this type of interaction is very efficient at the same time it increases very rapidly with (Z) this type of interaction unlike Compton Effect which in turn reduces the contrast on the film.**

***Compton Effect depends mainly on the number of electrons in the material.**

***As the x-ray energy increases photoelectric effect decreases and Compton Effect increases.** (Fig.16.14)

***At low energy ($_{e.g.}$ 30 keV) bone absorbs x-ray 8 times more than soft tissue due to photoelectric effect and that was because of the atomic №.of bone is higher than soft tissue (Z=13) and for soft tissue is (Z=7.4). So it is easy to get a good contrast between bone and soft tissue. (Why?)**

**Owing to the low atomic №.for soft tissue, Compton Effect interaction is the predominant interaction in the range of diagnostic radiation even if working at**

**reasonably low x-ray energy still appreciable amount of Compton Effect present.**

**For this reason to establish a contrast between two soft tissues close in their atomic numbers is difficult to make this possible, contrast media were introduced; these are of high atomic number* which can absorb x-ray more than the soft tissue.**

- **Compound contain iodine are often injected into the blood stream to show arteries (fig.16.15a).**
- **An oily mist containing iodine is sometimes sprayed into lungs to make the airways visible (fig.16.15b).**
- **Radiologist give barium compound orally to see parts of the upper gastrointestinal tract (upper G/T).**
- **Barium enemas to view the other end of (G/T) (fig.16.15c).**

**Since gases are poorer absorbers of x-ray than liquids and solids, it is possible to use air as a contrast medium. When pneumoencephalogram is taken, air is used to replace some of the fluid in the ventricles of the brain (fig.16.16).**

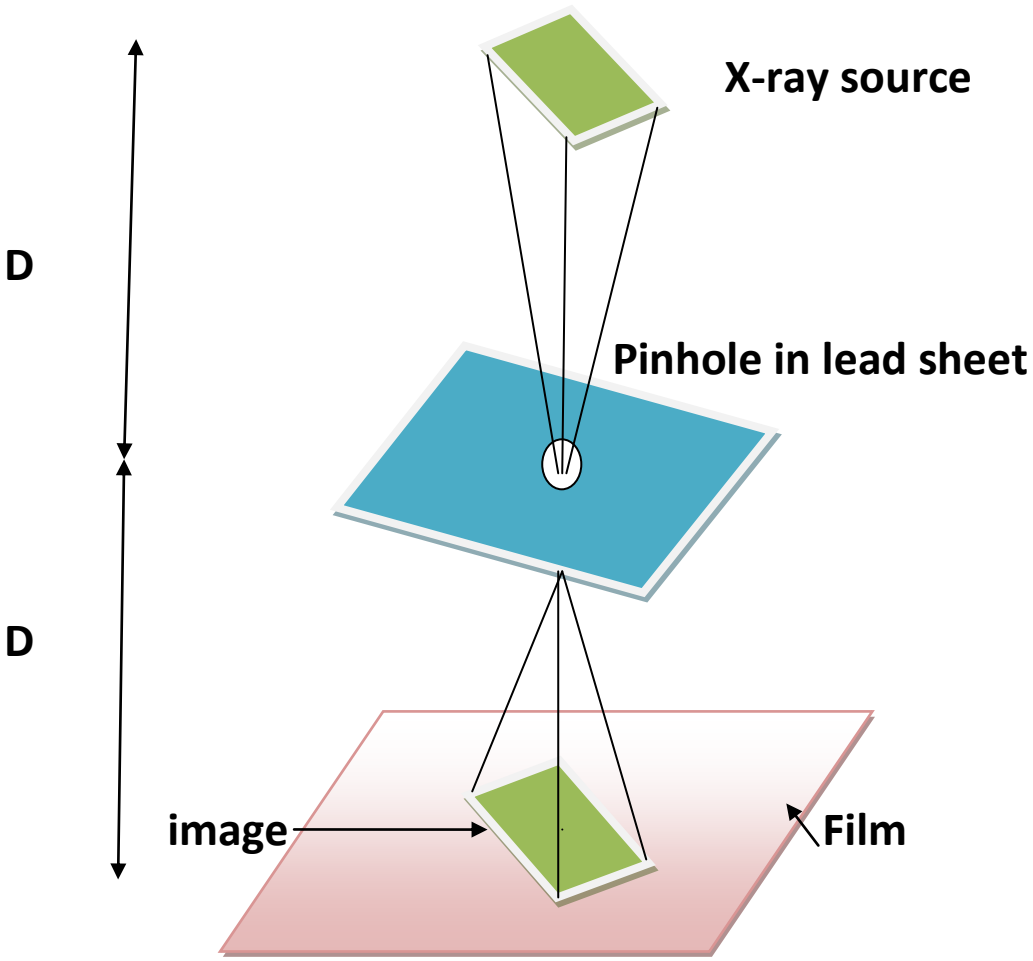
***To obtain more information from radiograph subtraction is used. In this way, two x-ray images are taken; one is plain and the other with contrast media.**

A negative tone of them is taken and put over the other, on this way only image appear is that the one with contrast media will be seen clearly.

## Viewing the focal spot:-

This is done by simple procedure.

A sheet of lead with a pinhole in the middle is placed in midway between the focal spot and parallel to the film, and then an exposure is given to the film. In doing so, the x-ray beam passing through the pinhole will cast the focal spot shadow (fig.16.12).



**This is useful in:-**

1. **Inspecting the size of the focal spot.**
2. **The x-ray uniformity which indicate the target surface smoothness.**

**Also the shape, if it is not circular, it may indicate the filament target misalignment.**

## Half value layer (HVL):-

**The HVL of an x-ray beam is the thickness of a given material that will reduce the beam intensity by one half** (fig.16.10, 16.11).

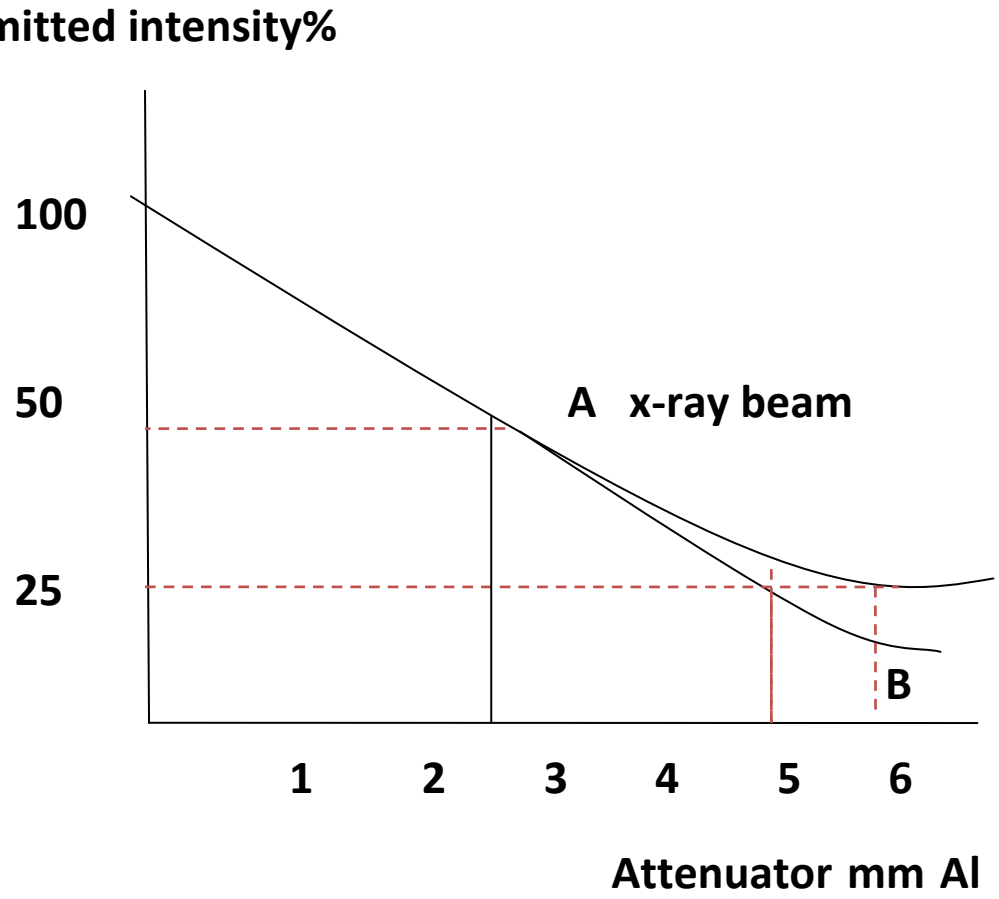
**The second HVL is defined the same as the first but is taken for the beam of x-rays emerging from the first HVL.**

$$hvl = \frac{0.693}{\mu}$$

**For an x-ray beam the second HVL is usually thicker than the first HVL because the beam emerged from the**

**first HVL is harder (contains more high energy radiation) than the original beam because much of low energy has low penetration power or highly absorbed.**

***for this reason the mono energetic beam has its first HVL=it's second HVL.**




***B** monoenergetic x-ray

***A x-ray beam**

## The equivalent energy for an x-ray beam:-

**It's the energy of mono energetic x-ray beam that has the same HVL of the ordinary (multi energetic) x-ray beam as shown in x-ray spectrum (fig/16.11).**

# Filters:-

**The purpose of filtration is to reduce or eliminate the low energy radiation from the x-ray beam. This low energy radiation which has no benefit in producing an x-ray radiograph, but it will be absorbed within the patient without any benefit in producing a good radiograph.**

**Although filters can reduce the low radiation energy but has also an effect on the higher energy (i.e. reducing the intensity of high energy) but the effect on the low energy radiation is much higher. (fig.16.28). Increasing the x-ray exposure should compensate this reduction in the intensity.**

**Filters are always fitted in the x-ray tube.**

## Intensifying screen:-

**It is composed from:-**

1. **Fluorescent crystals: - such as calcium unstated ($CaWO_4$) that absorbs x-ray and convert it to visible or UV-light.**
2. **Cardboard which is covered by thin layer of the fluorescent material. It is used with film and light sensitive emulsion.**

**When these screens are used with double-coated film, two of them are needed one at front (front screen) and the other at the back (back screen).**

**These two screen are installed into the film cassette such that, (1) the film will be in between and (2) held firmly and (3) in close contact with the film. Using felt at the back screen or using vacuum cassettes to hold screen in close contact with the film (fig.16.25). . If screens are not in close contact they will give high amount of unsharpened or blurring.**

**The benefit of intensifying screens is to reduce exposure. It has a disadvantage of given a certain degrees of unsharpness.**

**Screens have different intensification factors, are slow, normal &fast. For normal and fast screens can reduce**

**exposure more than 30 times compared with non-screen films.**

**The faster the screen the more the unsharpness:-**

**Good screens those, which can (1) absorb much of the x-rays and (2) has conversion factors from x-rays to UV-light.**

## Fluoroscopy:-

**1-The conventional fluoroscopy, is composed from screen coated with fluorescent material, it gives yellow when struck by x-ray.**

**The screen is covered by lead glass, which absorbs all the transmitted radiation.**

**Because the light emitted from the fluoroscopic screen is weak, the radiologist has to view the image with his night vision (rods), which it is 1000 times more sensitive than (cones) for day vision. To do this, radiologist uses red goggles for night adaptation because rods are insensitive to the red light. Some radiologist in some cases increase the x-ray exposure such as (KV or MA) which makes the**

**image brighter, but in this way the x-ray hazard is increased for both patient and the operators.**

**Fluoroscopy were used in shoe stores as gimmicks to help sell shoes ,but it is found to(1) give large dose of unnecessary radiation to the population and (2) even more hazardous that is directed upwards exposing the gonads for relatively large doses which may increase the amount of radiation.**

**This is against the protection rules so until 1960 it was stopped.**

**2. The image intensifier :-**

**As the conventional fluoroscopy gives very weak light a device called the image intensifier has been constructed, *it Consist of fluorescent screen on which the x-ray pattern is directed as the conventional fluoroscopy (fig.16.32).**

**The corresponding pattern light emitted from this screen is incident upon a second screen (photocathode) which emits electron (by photoelectric effect) and the photocathode is in intimate contact with the fluorescent screen.**

**The intensity pattern of the electrons emitted from the photocathode will correspond exactly with the pattern of light incident upon it, and therefore to the pattern of x-ray beam.**

**The electrons emitted from the photocathode are accelerated across evacuated envelope (tube), by voltage about 25KV applied between the photocathode and the fluorescent viewing screen (fig.16.32).**

**The light produced by absorption of the increased energy electrons in the viewing screen is very much brighter then the light emitted from the initial screen (about 1000 times brighter) and this is in fact sufficiently bright to be seen by cone vision which has better resolving power than rods, but it does not result in a significant reduction in patient dose.**

**The increased brightness also makes it possible to take movies (scines) of the fluoroscopic images.**

**The movie camera is sometimes replaced by TV camera.**

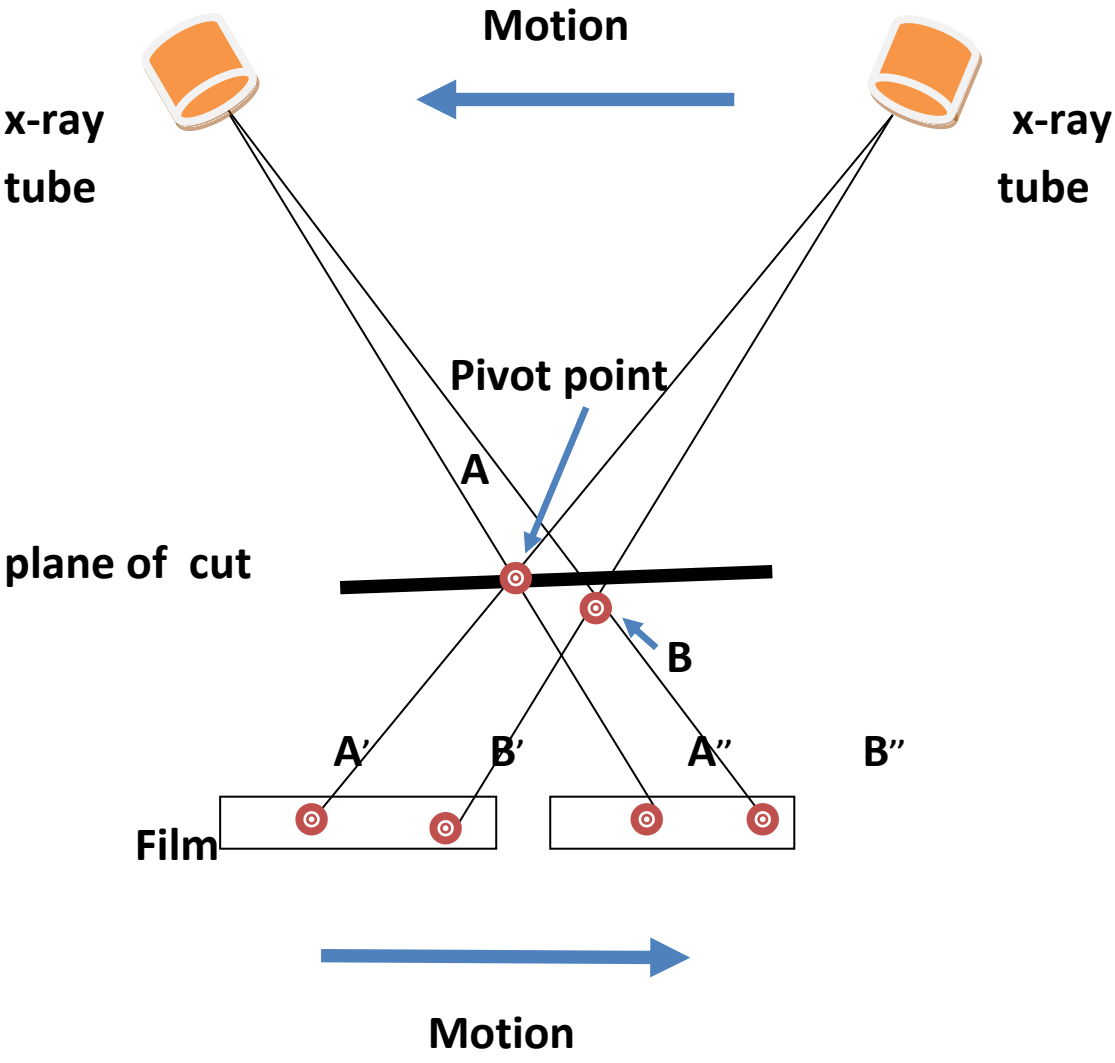
**This can enable us to (1) video tape recording for latter study or (2) transfer the image to TV monitors during fluoroscopy (fig.16.33).**

## TOMOGRAPHY - X-ray of the body

**In taking ordinary radiography objects in the path of x-ray beam are superimposed the shadow of organ of interest may be masked or disturbed by other organs. Tomography is a technique that to show one**

plane clearly and blur out all shadows over and under this plane of interest (Plane of Cut) also called tomography section.

The structure of conventional linear tomography is an x-ray tube and a film are mechanically linked and move so that the shadows of structures at chosen level in the patient (the plane of cut) are cast at the same points on the film throughout the synchronized movement of the tube and the film (fig. 16.34).



**Shadows of points above and under the plane of cut will be blurred because it will not cast their shadows on the same points on the film during the movement of the x-ray tube and the film.**

**But it will move along the film during exposure and cause blurring. In this way we can see only the plane of cut clearly. The plane of cut will be moving around.**

**This type of tomography (is linear tomography) (fig. 16.34), it may introduce artifacts or not good blurring in cases such as, for example, if an extended organ laying at the same direction of the tomography movement will not be blurred completely, for this reason and others a more complicated movements for tomography has been used, these are elliptical and cycloid movements. (Fig. 16.36).**

**Linear tomography gives longitudinal section other types called (Transverse axial tomography) can give a transverse plane of cut by changing the direction of the x-ray beam and the film position or in planning of cancer therapy.**

## COMPUTERIZED AXIAL TOMOGRAPHY (CAT) OR (CT-SCANNERS). FIG (16.37)

**The conventional tomography was dramatically improved in 1972, this type of tomography does not use an x-ray film, and it consists of an x-ray tube works at relatively high potential (~140KV).**

**The opposite side of the tube a scintillation detector is placed which can register the attenuation for x-ray beam then stored in the computer memory. The x-ray beam is narrow, very well collimated and filtered.**

**When the scan started at ZERO-angle, a single beam of x-ray attenuation is taken and registered, then the detector and the tube move side way and another x-ray line attenuation is registered , this procedure is repeated until 140-156 lines. The whole procedure is repeated over180°.**

**In practice each scan is double: the attenuation pattern for two adjacent slices is taken simultaneously and displayed on two separate monitors. All these attenuation will be registered by angle and position in the computer and a simultaneous processing of all the registered attenuations is carried out by the computer**

**and projected on a screen as a picture according to the registered attenuation.**

**The total time for scan takes about 4 min. This long time is not suitable for scans that need breathe holding. It is difficult to hold the breath more than 30 sec, New generation of modern scanners now is being developed with a fan shape x-ray beam and multi detectors, these new generations scanners can finish the scan in less than 30 sec, latest generations scanners takes 1-2 sec.**

**The attenuations can be presented as numbers of a separate display the choice of the max. number for compact bone is +500 ,0 and (-500) for water and air respectively, this scale is taken arbitrary and called CT-number form which the type of lesion can identified by using these numbers .(fig .16.38).**

**Xeroradiography: The principle of this radiography that is consists of selenium coated plate dept in a light tight cassette, the plate is positive charged and because the selenium is an insulator charges will stay without movement , when an x-ray pattern fall on it electrons will be released and**

**neutralize the positive charges and a charge pattern will be on the selenium sheet according to the x-ray pattern.**

**When a negatively charged powder ink sprayed on the selenium sheet it will adhere with the positive charge the more ink accumulation so the exposed part will have less charge than less ink on it and will be brighter so the picture is positive. It can also be negative picture if the ink is positively charged.**

**After this stage the overall sheet of selenium is neutralized the ink will be loosely attached with the selenium sheet (fig . 16.42).**

**A plastic coated paper is put together on the surface of the selenium sheet, the powder will be transferred to the paper and the picture is printed on the paper then the paper is heated to fix the powder on the paper not to smudge.**

## Advantages and disadvantages of xeroradiography :-

**Although xeroradiography has low contrast but it can give sharp radiograph due to the edge enhancement effect. This effect is due to the charge distortion on the edge between two differently exposed parts and consequently more powder will be accumulated on the edge giving sharp edge or edge enhancement. This is in addition to the high latitude for xeroradiography which can give acceptably densities even for thick parts.**

**One main disadvantage is that xeroradiography less sensitive than ordinary radiography so it needs higher exposures sometimes ten times greater than ordinary radiography.**

# PHYSICS OF EYES AND VISION

The sense of vision consists of three major components:

1-The eyes that focus an image from outside world on the light sensitive retina.
2-The system of millions of nerves that carries the information deep into the brain.
3-The visual cortex-that part of the brain where, it is all put together.

Blindness results if any one of the parts does not function.

The physics of the first part far better than the physics of the other two parts.

# FOCUSING ELEMENTS OF THE EYE

**The eye has two major focusing components:**

**1-The cornea is a fixed focus element.**

**2-The lens is variable in shape and has the ability to focus objects at various distances**.

**The cornea focuses by bending (refracting) the light rays. The amount of bending depends on the curvatures of its surfaces and the speed of light in the lens compared with that in the surrounding material. The index of refraction is nearly constant for all corneas, but the curvature varies considerably from one person to another and is responsible for most our defective vision.**

**1-If the cornea is curved too much the eye is near sighted.**

**2-Not enough curvature results in far sightness.**

**3-Uneven curvature produces astigmatism.**

**The lens has a flexible cover that is supported under tension by suspension fibers.**

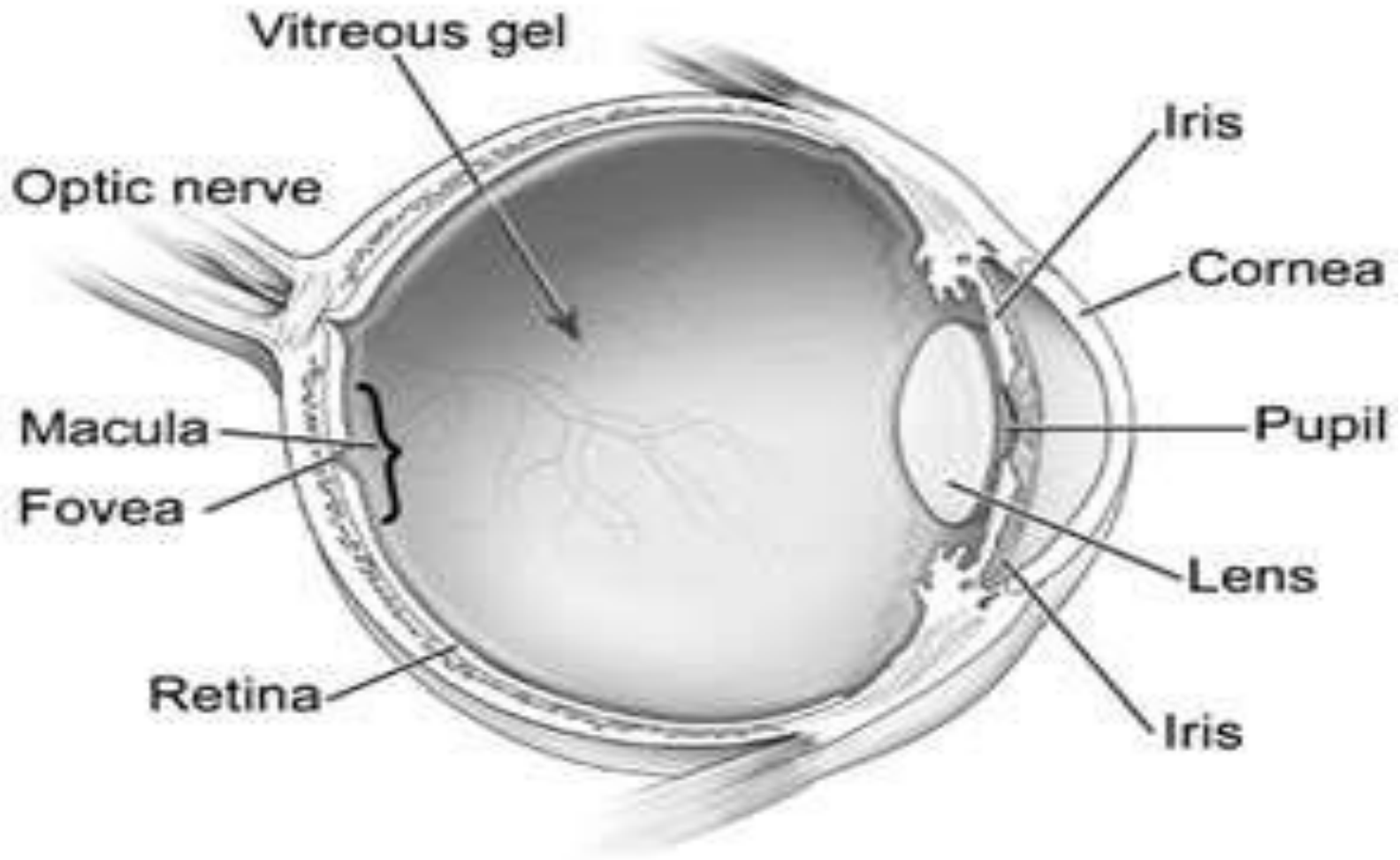
**1-When the focusing muscle of the eye is relaxed this tension keeps the lens somewhat flattened and adjusted to its lowest power, and the eye is focused on distant objects. The point at which distant objects are focused when the focusing muscle is relaxed is called the far point.**

**2-For a near sighted, the circular muscle around the lens contracts into a smaller circle and takes some or all of the tension off the lens. The lens then has a greater focusing power, the closest point at which objects can be focused when the lens is its thickest is called the near point.**

**3-Young children have very flexible lenses and can focus on very close objects. The ability to change the focal power of the eye is called accommodation.**

**4-As people get older, their lenses lose some accommodation, presbyopia (old sight) results when the lens has lost nearly all of its accommodation.**

# SOME OTHER ELEMENTS OF THE EYE



**Pupil is the opining in the center of the iris where light enters the lens. It appears black because essentially all of the light that enters is absorbed inside the eye. Under average light condition, the opining is about 4mm in diameter. It can change from about 3mm in diameter in bright light to about 8mm in diameter in dim light. The iris does not respond instantly to a change of light levels; about 300 s are needed for it fully open, and about 5 s are required for it to close as much as possible.**

**Aqueous humor fills the space between the lens and the cornea. This fluid, mostly water, is continuously being produced, and the surplus escapes through a drain tube.**

**Vitreous humor is a clear jelly that fills the large space between the lens and the retina. It helps keep the shape of the eye fixed and essentially permanent.**

**Sclera is the tough, white, light-tight covering over all of the eye except the cornea.**

# THE RETINA-THE LIGHT DETECTOR OF THE EYE

**The retina, the light sensitive part of the eye, converts the light images into electrical nerve impulses that are sent to the brain.**

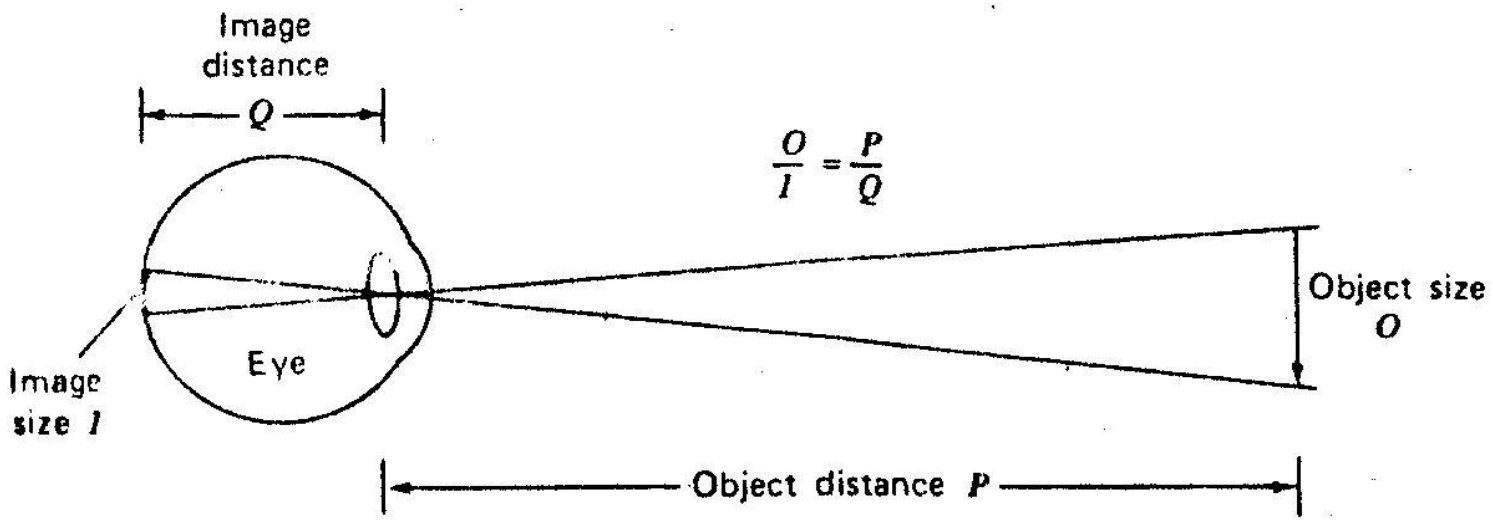
**The absorption of a light photon in photoreceptor triggers an electrical signal to brain-an action potential. The light photon apparently cause a photochemical reaction in the photoreceptor which in some way initiates the action potential. The photon must be above a minimum energy to cause the reaction.**

**1-Infrared photons have insufficient energy and thus are not seen.**

**2-Ultraviolet photons have sufficient energy, but absorbed before they reach the retina and also are not seen.**

**The retina covers the black half of the eyeball. While this large expanse permits useful" warning" vision over a large angle, most vision is restricted to a small area called the macula lutea, or yellow spot. All detailed vision takes place in a very small area in the yellow spot (~0.3mm in diameter) called the fovea centralis .**

**The image on the retina is very small. A convenient equation for determining the size of image on the retina comes from the ratios of the lengths of the sides of similar triangles.**




I: is image size Q: is image distance

O: is object size P: is object distance

Thus we can write O/P=I/Q

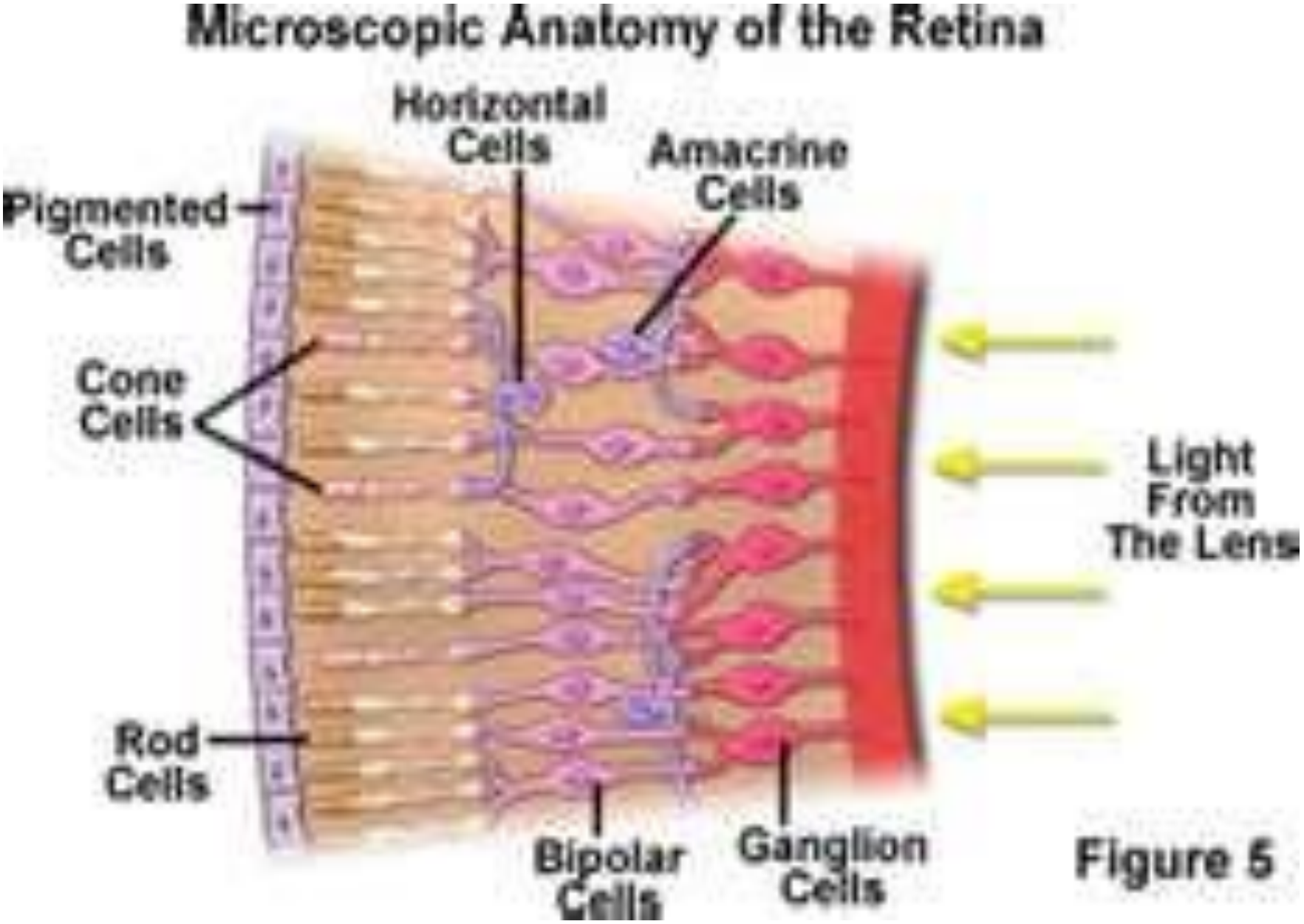
**EXAMPLE:**

**How big is the image on the retina of a fly on a wall 3.0m away? Assume the fly is 3mm in diameter and Q=0.02m.**

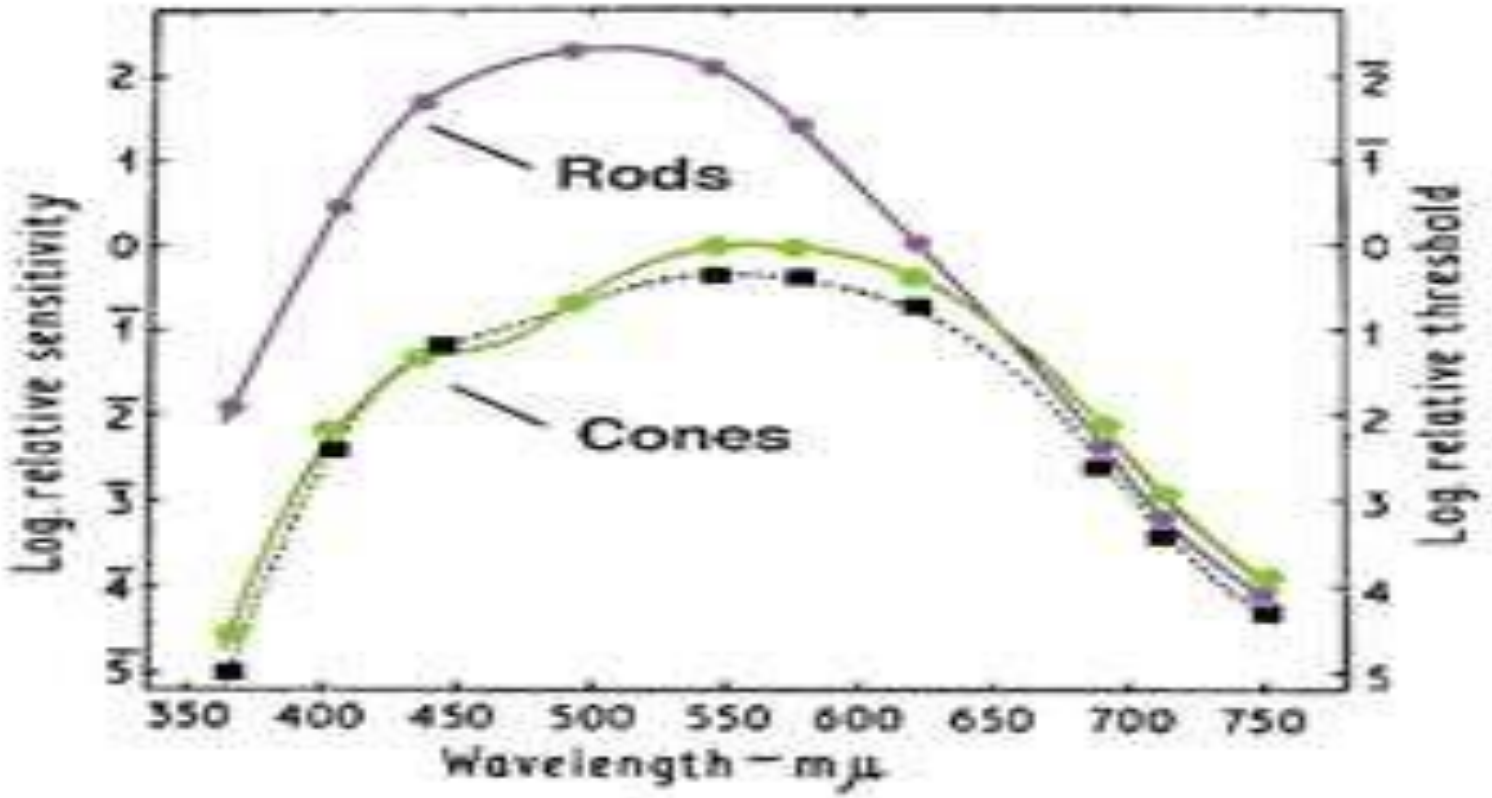
$$I = 0.02/3 \times 0.03 = 2 \times 10^{-5}m = 20\mu m$$

**There are two general types of photoreceptors in the retina: the cones and the rods,the rods and cones are distributed symmetrically in all directions from visual axis except in one region-blind spot .**

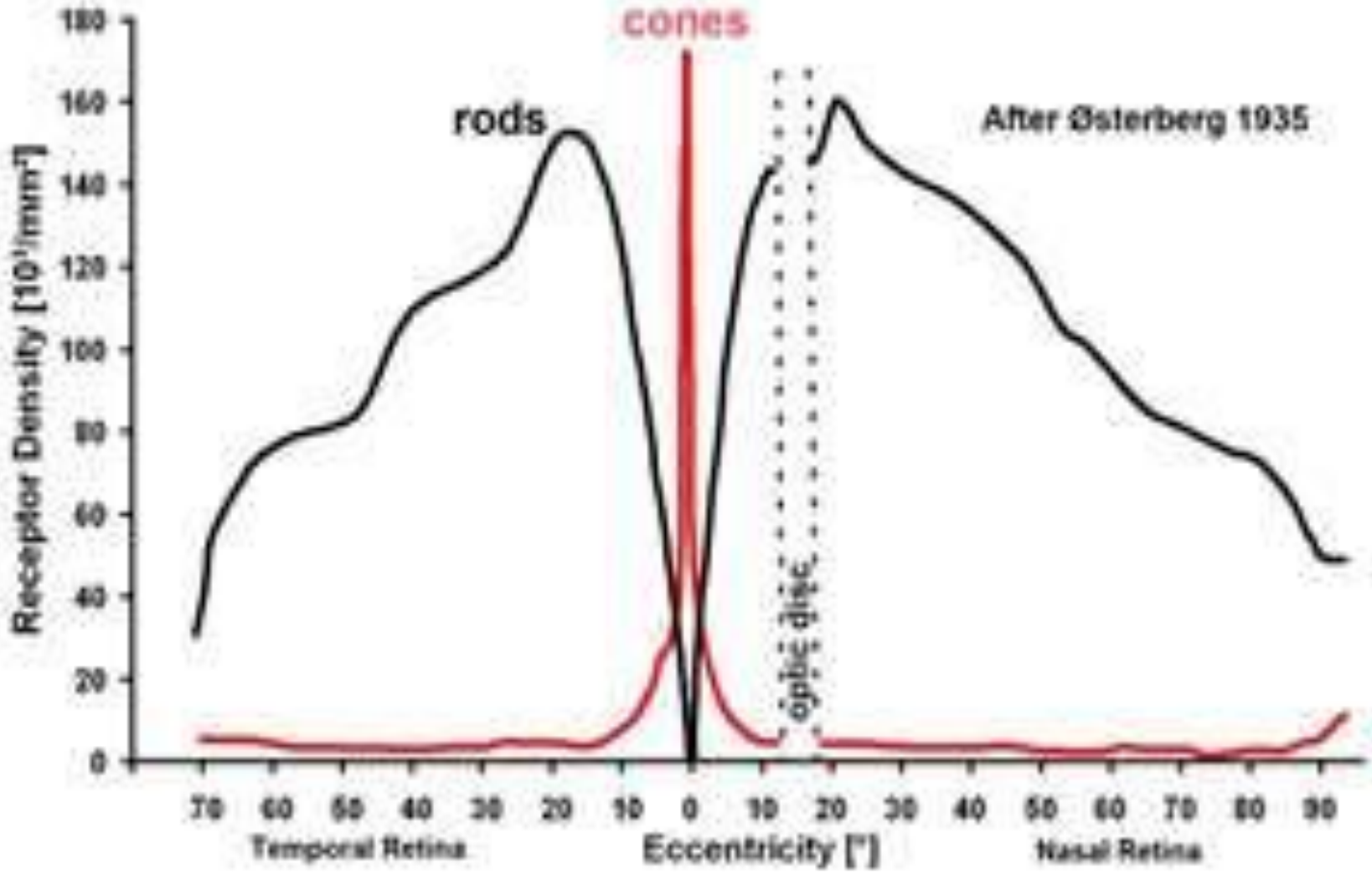
**Throughout most of the retina the cones and rods are not at the surface of the retina but the lie behind several layers of the nerve tissue through which the light must passes.**


Microscopic Anatomy of the Retina
Horizontal Cells
Amacrine Cells
Pigmented Cells
Cone Cells
Light From The Lens
Rod Cells
Bipolar Cells
Ganglion Cells
Figure 5

**The cones are used for daylight, or photopic, vision. With we can see fine detail and recognize different colors. The cones are found in the fovea centralis. Each of the cones in the fovea has its own telephone line to the brain. The cones are not uniformly sensitive to all colors but have a maximum sensitivity at about 550 nm in the yellow – green region.**




**. THE RODS ARE USED FOR NIGHT, OR SCOTOPIC, VISION AND FOR PERIPHERAL VISION. THEY ARE NOT UNIFORMLY DISTRIBUTED OVER THE RETINA BUT HAVE A MAXIMUM DENSITY AT AN ANGLE OF ABOUT $20^{O}$.**


cones
rods
After Østerberg 1935
optic disc
Receptor Density [10³/mm²]
180
160
140
120
100
80
60
40
20
0
70 60 50 40 30 20 10 0 10 20 30 40 50 60 70 80 90
Temporal Retina
Eccentricity [°]
Nasal Retina

**That is, if you are looking at the sky at night, the light from a faint star displaced $20^o$ from your line vision will fall on the most sensitive area of your retina. If you look directly toward the faint star, its image will fall on your fovea which has no rods and you will not see it.**

**The rods are .**

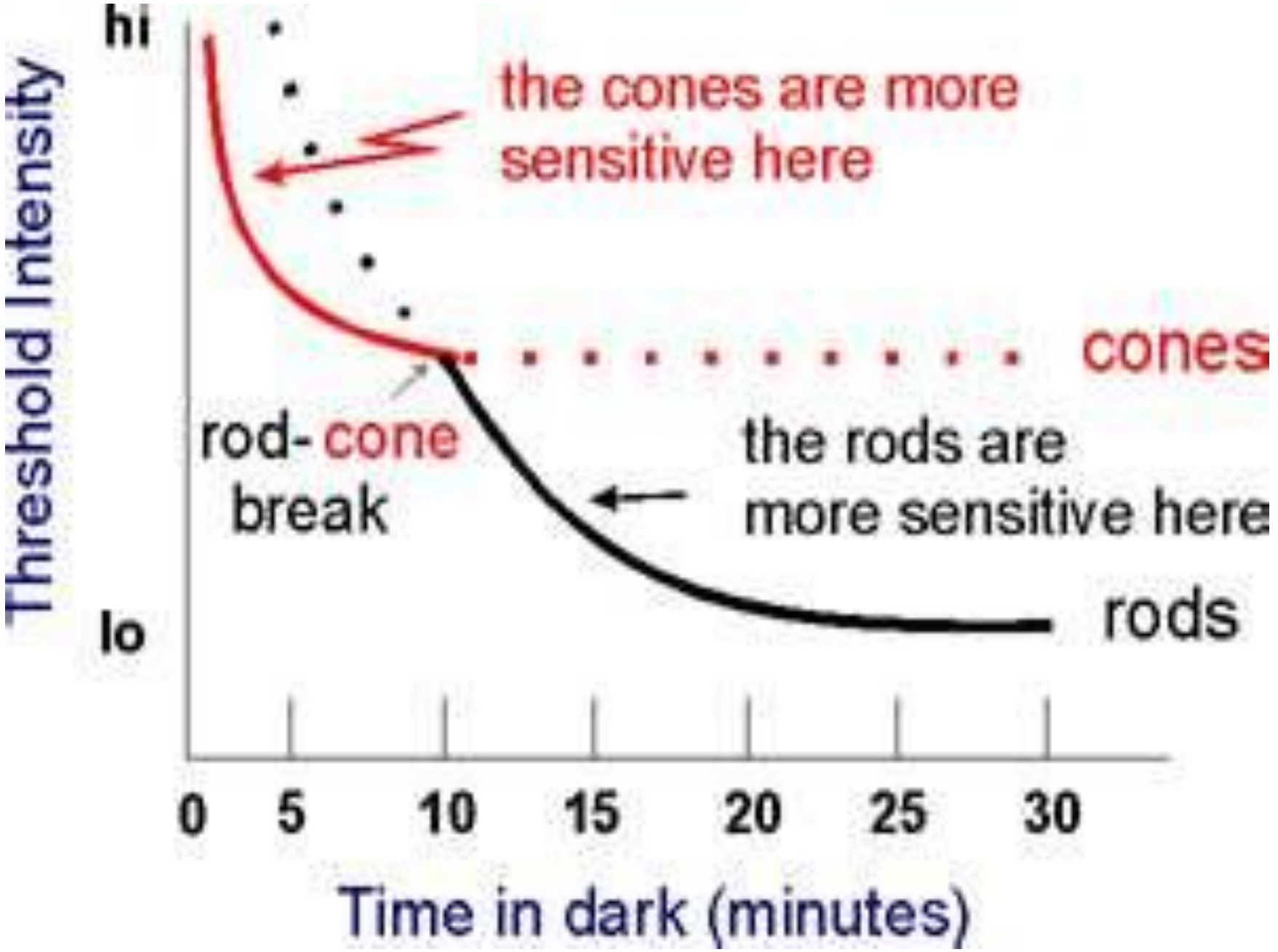
**most sensitive to blue-green($\sim 510nm$)**

**The rods and cones are equally sensitive to red light (650 to 700nm).**

**Dark adaptation:** **is apparently the time needed for the body to increase the supply of photosensitive chemicals to the rods and cones.**

**The eyes do not have their greatest sensitivity to light under photopic conditions, if the light level suddenly decreases by a factor of 1000 we are momentarily "in dark", but after a few minutes we are able to see many of details that were not visible when it first became dark.**

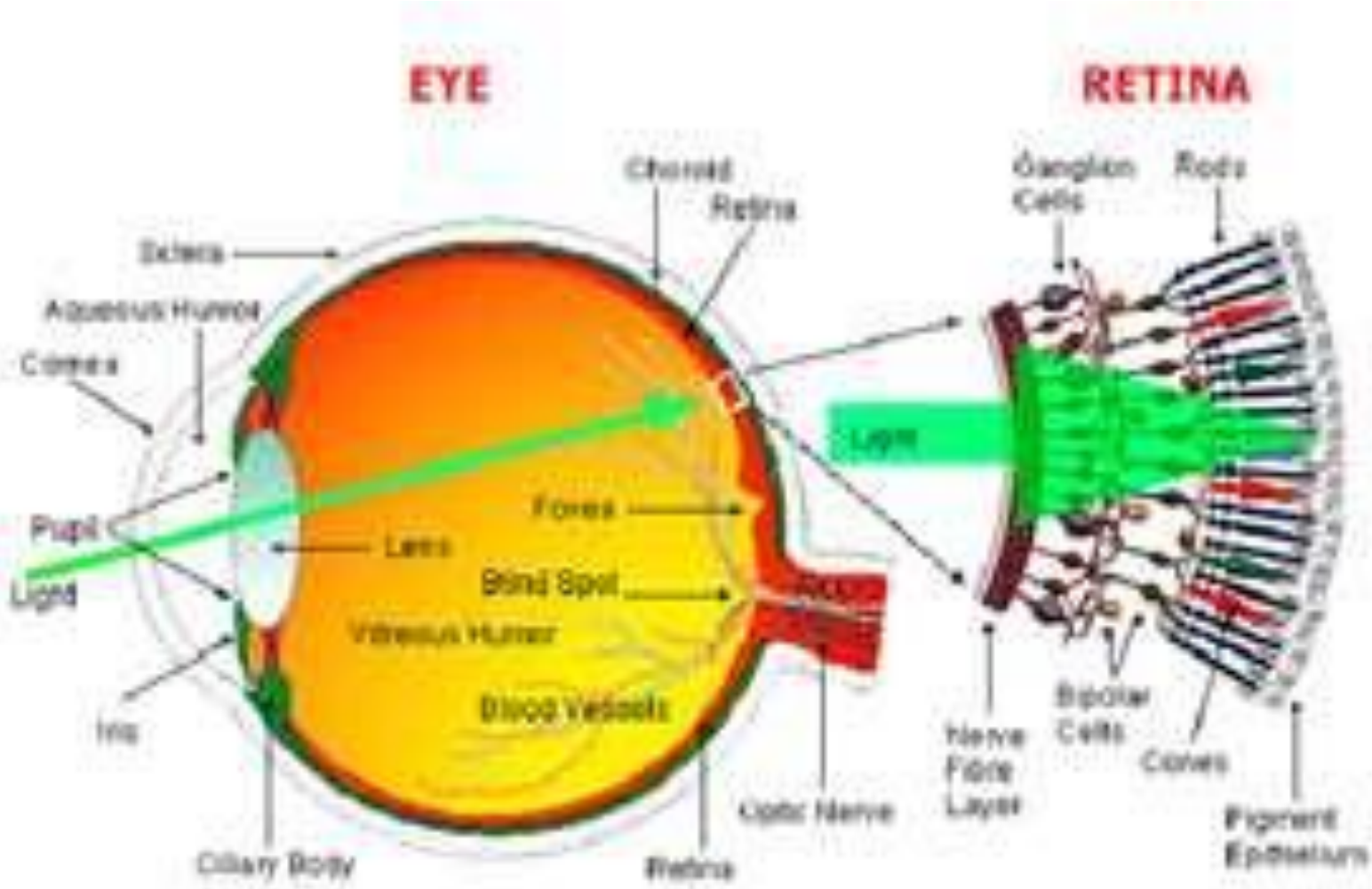
**The cones adapt most rapidly; after about 5 min the fovea centralis has reached its best sensitivity. The rods continue to dark adapt for 30 to 60min, although most of their adaptation occurs in the first 15 min.**


hi
lo
Threshold Intensity
the cones are more sensitive here
cones
rod-cone break
the rods are more sensitive here
rods
0
5
10
15
20
25
30
Time in dark (minutes)

# Blind spot:

**THAT HAS NEITHER RODS NOR CONES.**

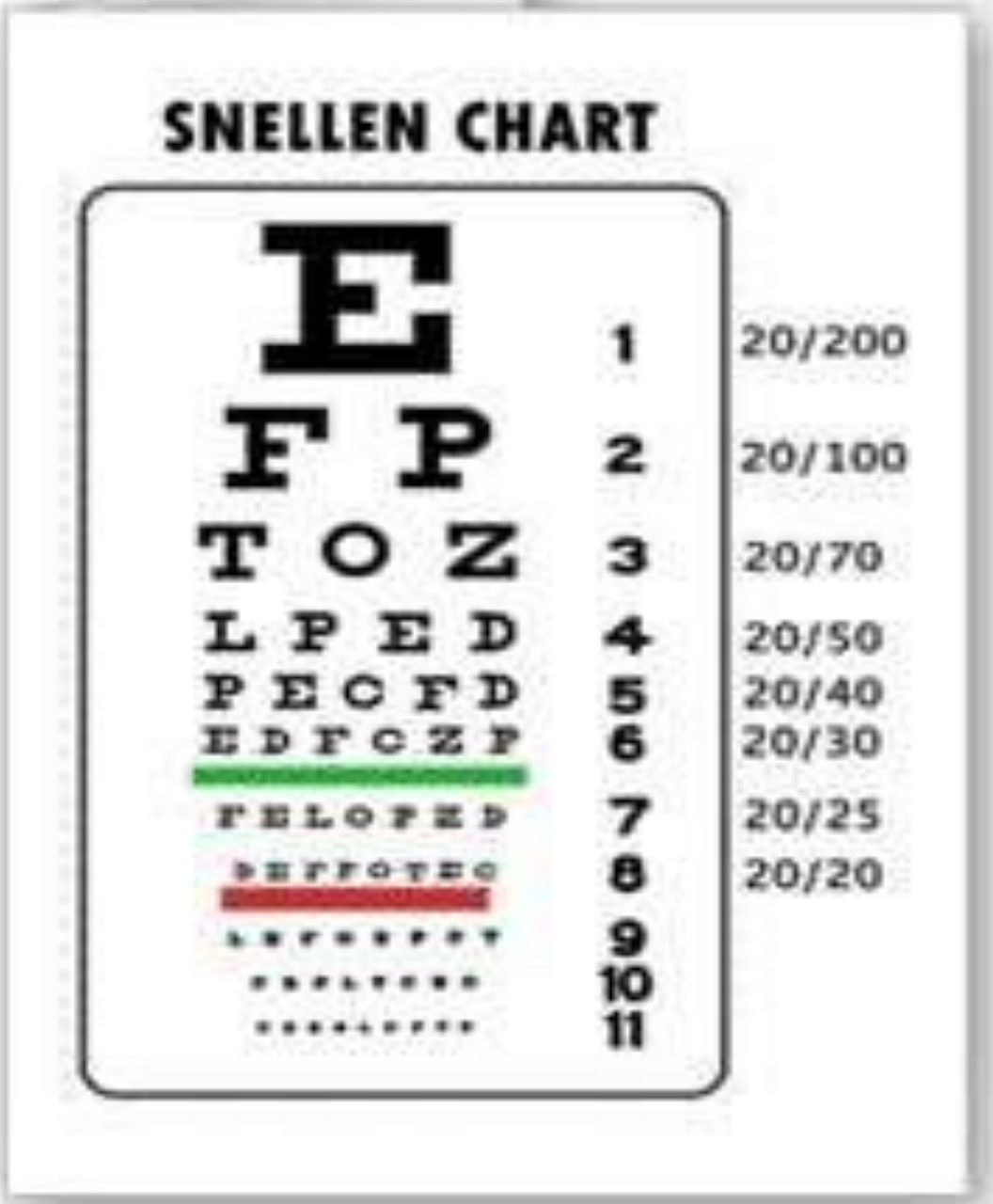
**THAT THERE IS A REGION FROM ABOUT $13^{O}$ TO $18^{O}$**




Adapted from WEBVISION http://webvision.med.utah.edu/

## HOW SHARP ARE YOUR EYES

**The optometrist usually uses a snellen chart to test visual acuity. If he tells you that your eyes test normal at 20/20, he means that you can read detail from 20 ft that person with good vision can read from 20 ft. If your eyes test at 20/40, you can just read from 20 ft the line that a person with good vision can read from 40 ft.**


SNELLEN CHART
E
F P
T O Z
L P E D
P E C F D
E D F C Z P
F E L O P E D
D E F P O T E C
1
2
3
4
5
6
7
8
9
10
11
20/200
20/100
20/70
20/50
20/40
20/30
20/25
20/20

**The ability of the eye to recognize separate lines also depends on the relative "blackness "and "whiteness" , the contrast between two areas is defined as optical density OD**

$$OD = \text{Log}\,(I_o/I)$$

**Where $I_o$ is the light intensity without absorber and I is intensity with absorber.**

**EXAMPLE:** A piece of film that transmits 10% of the incident light has an optical density

$$OD = Log(1/0.1) = 1.0$$

**EXAMPLE:** A film that absorbs 99% of the light has an optical density

$$OD = Log(1/0.01) = 2.0$$

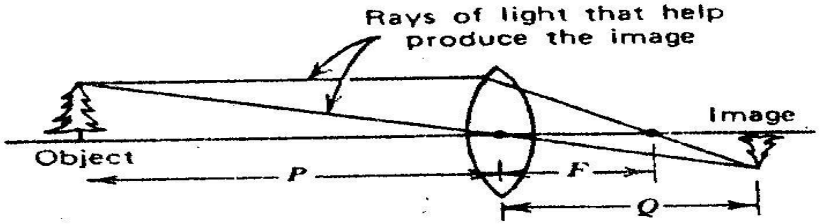
An OD=3 means that only 0.001 of the light transmitted.

# DEFECTIVE VISION AND ITS CORRECTION

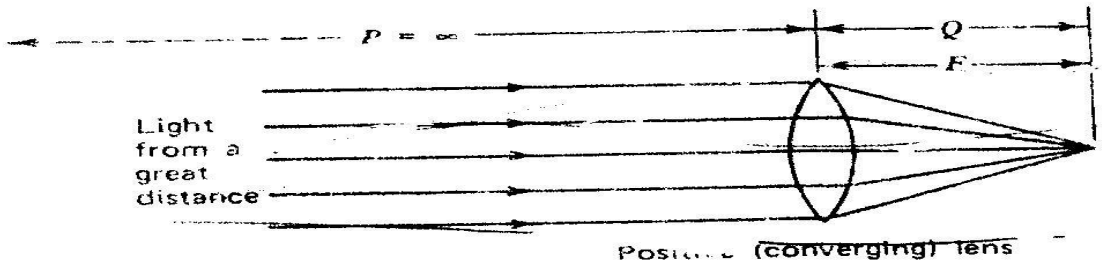
There is a simple relationship between the focal length **F**, the object distance **P**, and the image distance **Q** of the lens

$$\mathbf{1/F = 1/P + 1/Q}$$

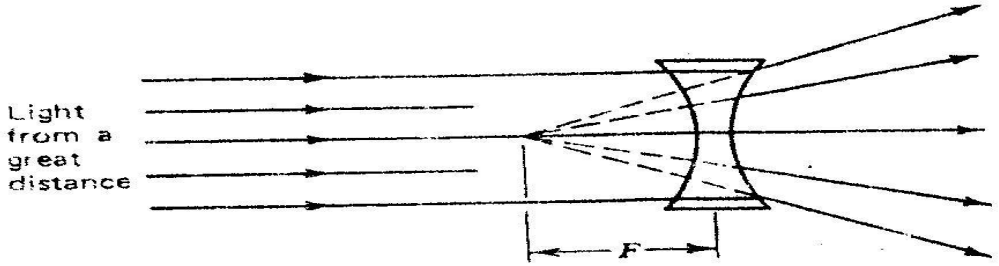
If **F** is measured in meters, then **1/F** is the lens strength in diopters **(D).**


Rays of light that help produce the image
Image
Object
P
F
Q

(a)


P = ∞
Q
F
Light from a great distance
Positive (converging) lens

(b)


Light from a great distance
F
Negative (diverging) lens

(c)

The ability of the eye to focus on objects over a wide range is called accommodation.

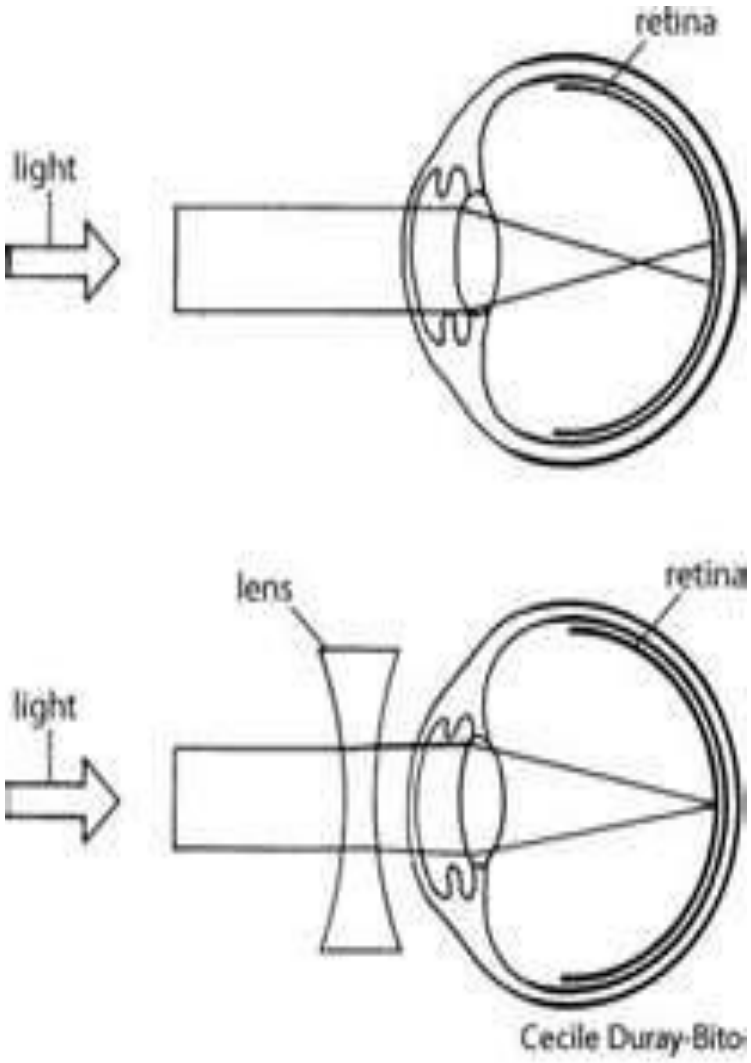
Power of accommodation of normal eye $= \frac{1}{F}$

$$= \frac{1}{near\ point} - \frac{1}{far\ point}$$

$$= \frac{1}{0.25m} - \frac{1}{\infty} = 4 \text{ Diopter}$$

**The eyeball is too long, and parallel rays are focused by the relaxed eye to a position in front of the retina. Only near objects can therefore be seen clearly. This defect can be corrected by diverging lenses. If the spectacle lens is chosen to have a focal length equal in magnitude to the distance to the far point (F), then parallel rays striking the spectacles appear to the eye to diverge from the far-point. Note that the least distance of distinct vision for the spectacled eye is no longer d but increased to x.**

**MYOPIA**

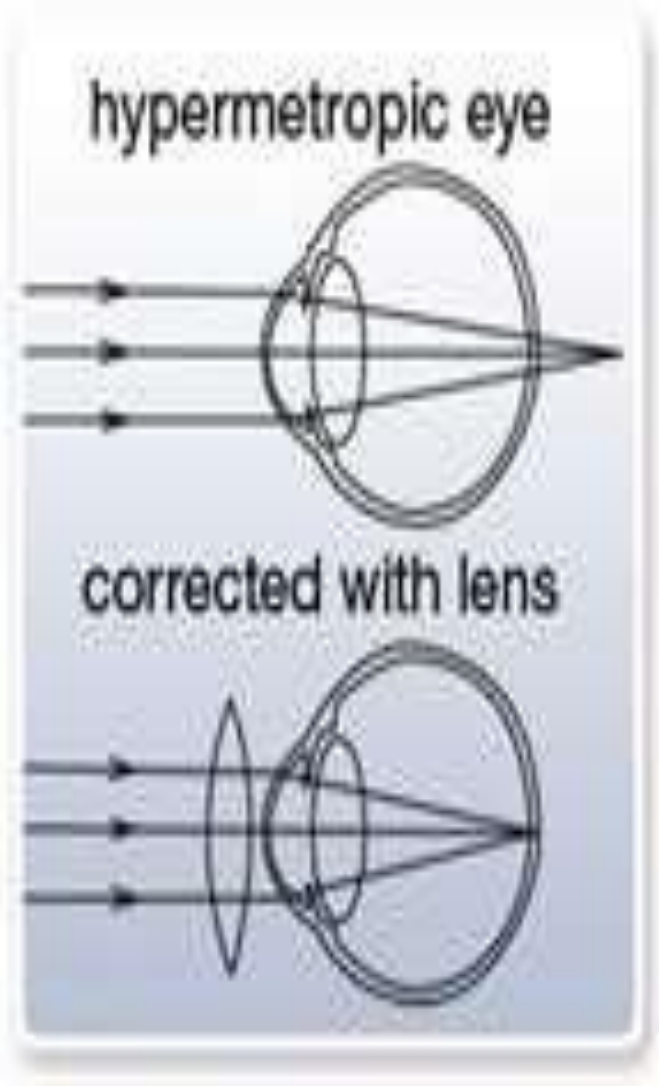


where $\frac{1}{-F} = \frac{1}{x} - \frac{1}{d}$

**An object at distance x must produce a virtual image at d in the spectacle lens in order just to be brought to focus by the eye.**

# HYPERMETROPIA:

**This is the opposite effect. The eyeball is too short and parallel rays are focused to a point behind the retina, this defect is corrected by using converging spectacle lenses, if the near point is at $d^1$. Then an object at d requires the lens to produce a virtual image of it at $d^1$ which will then be visible to the fully accommodation eye in the other words the focal length of the spectacle lenses must be F.**



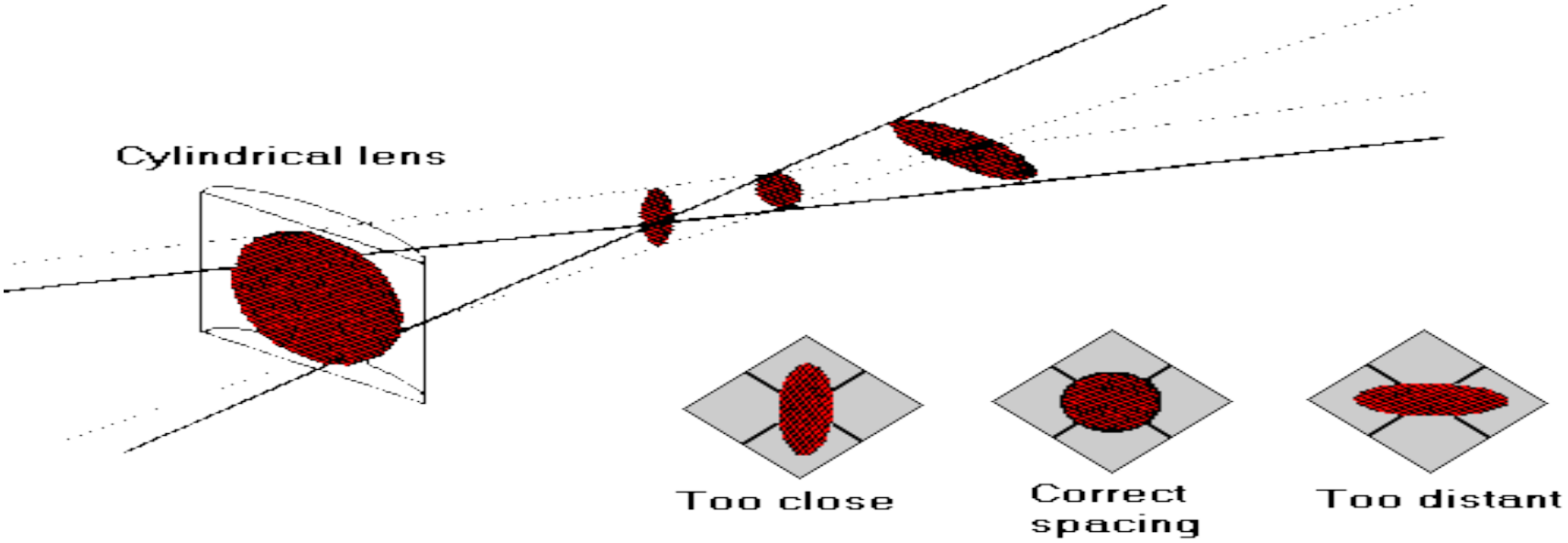

**Where** $$\frac{1}{F} = \frac{1}{d} - \frac{1}{d^1}$$

**PRESBYOPIA:**

**As people get older the cillary muscles weaken and lens losses some of its elasticity . The power of accommodation diminishes with age. This defect is corrected by two parts of lenses upper half of each lens is diverging and corrects the myopia when the wears is looking ahead at distance objects, the lower half corrects the presbyopia with a suitable converging lens, and the wearer looks through this part when reading**

# ASTIGATISM

When astigmatism is present, point objects do not form point images on the retina. This is normally due to the corneas unequal curvature in different directions. If the curvature is greater in a horizontal section than in the vertical section, rays brought to a focus more quickly in the horizontal than in the vertical plane. The defect is corrected by the use of cylindrical spectacle lenses.



**EX 1:** A man has a near point 50cm and far point infinity, what is his useful accommodating power.

$$P = \frac{1}{near\ point} - \frac{1}{far\ point}$$

$$= \frac{1}{0.5m} - \frac{1}{\infty} = 2\ Diopter$$

**EX 2:** What spectacle lenses would be prescribed for the man of example 1.

$$1/F_{\text{corrected}} = 1/n.p_{\text{for normal eye}} - 1/n.p_{\text{defected}}$$

$$1/F_{\text{corrected}} = 1/0.25m - 1/0.5m = 2 \text{ Diopter}$$

$$F = 1/2 \text{ Diopter} = 0.5m = 50cm$$

**EX 3:** A myopic male has near and far point of 20cm and 250 cm respectively. What spectacle lens is prescribed for his defect and where is his near point.

$$1/F_{\text{corrected}} = 1/f.p_{\text{for normal eye}} - 1/f.p_{\text{defected}}$$

$$1/F_{\text{corrected}} = 1/\infty - 1/2.5m = -0.4 \text{ Diopter}$$

$$F = -2.5m \qquad \text{the lens is diverging}$$

The near point when wearing the spectacles will be

$$1/F_{\text{corrected}} = 1/n.p_{\text{after wearing glass}} - 1/n.p_{\text{without glass}}$$

$$1/-2.5m = 1/n.p_{\text{after wearing glass}} - 1/0.2m$$

$$1/n.p_{\text{after wearing glass}} = 1/0.2m - 1/2.5m$$

$$= 5 \text{ Diopter} - 0.4 \text{ Diopter} = 4.6 \text{ Diopter}$$

$$n.p_{\text{after wearing glass}} = 1/4.6 \text{ Diopter} = 0.217m = 21.7cm$$

# Physics of nuclear medicine

# RADIOACTIVITY

Radioactivity, also known as radioactive decay, nuclear decay, nuclear disintegration and nuclear transformation, is a spontaneous process by which an unstable parent nucleus emits a particle or electromagnetic radiation and transforms into a more stable daughter nucleus that may or may not be stable. The unstable daughter nucleus will decay further in a decay series until a stable nuclear configuration is reached. Radioactive decay is usually accompanied by emission of energetic particles or γ ray photons or both.

All radioactive decay processes are governed by the same general formalism that is based on the definition of the activity $A(t)$ and on a characteristic parameter for each radioactive decay process, the radioactive decay constant $l$ with dimensions of reciprocal time, usually in s–1. The main characteristics of radioactive decay are as follows:

——The radioactive decay constant $\lambda$ multiplied by a time interval that is much smaller than $1/\lambda$ represents the probability that any particular atom of a radioactive substance containing a large number $N(t)$ of identical radioactive atoms will decay (disintegrate) in that time interval. An assumption is made that $\lambda$ is independent of the physical environment of a given atom.

——The activity $A(t)$ of a radioactive substance containing a large number $N(t)$ of identical radioactive atoms represents the total number of decays (disintegrations) per unit time and is defined as a product between $N(t)$ and $\lambda$, i.e.:

$$A(t)=\lambda N(t) \qquad (1.7)$$

The SI unit of activity is the becquerel (Bq) given as 1 Bq = 1 $s^{-1}$. The becquerel and hertz both correspond to $s^{-1}$, but hertz refers to the frequency of periodic motion, while becquerel refers to activity.

The old unit of activity, the curie (Ci), was initially defined as the activity of 1 g of $^{226}Ra$; 1 Ci ≅ $3.7 \times 10^{10}$ $s^{-1}$.

Subsequently, the activity of 1 g of $^{226}Ra$ was determined to be $3.665 \times 10^{10}$ $s^{-1}$; however, the definition of the activity unit curie (Ci) was kept as 1 Ci = $3.7 \times 10^{10}$ $s^{-1}$. Since the unit of activity the becquerel is 1 $s^{-1}$, the SI unit becquerel (Bq) and the old unit curie (Ci) are related as follows: 1 Ci = $3.7 \times 10^{10}$ Bq and, consequently, 1 Bq = $(3.7 \times 10^{10})^{-1}$ Ci = $2.703 \times 10^{-11}$ Ci.

Specific activity *a* is defined as activity *A* per unit mass *m*, i.e.:

$a = A/m = \lambda N/m = \lambda N_A/m$ (1.8)

where $N_A$ is Avogadro's number.

Specific activity *a* of a radioactive atom depends on the decay constant $\lambda$ and on the atomic mass number *A* of the radioactive atom. The units of specific activity are Bq/kg (SI unit) and Ci/g (old unit).

**Decay of radioactive parent into a stable or unstable daughter**

The simplest form of radioactive decay involves a radioactive parent nucleus P decaying with decay constant $\lambda_P$ into a stable or unstable daughter nucleus D:

$$P \xrightarrow{\lambda_P} D \qquad (1.9)$$

The rate of depletion of the number of radioactive parent nuclei $N_P(t)$ is equal to activity $A_P(t)$ at time *t* defined as the product $\lambda N(t)$ in Eq. (1.7). We, thus, have the following expression:

$$\frac{dN_{P(t)}}{dt} = -A_P(t) = -\lambda_P N_{P(t)} \qquad (1.10)$$

The fundamental differential equation in Eq. (1.10) for $N_P(t)$ can be rewritten in general integral form:

$$\int_{N_P(0)}^{N_P(t)} \frac{dN_{P(t)}}{N} = -\int_0^t \lambda_P \, dt \qquad (1.11)$$

where $N_P(0)$ is the initial condition represented by the number of radioactive nuclei at time $t = 0$.

Assuming that $\lambda_P$ is constant, Eq. (1.11) can be solved to obtain:

$$In\frac{N_{P(t)}}{N_{P(0)}} = -\lambda_P N_{P(t)} \qquad (1.12)$$

or

$$N_P(t) = N_P(0)e^{-\lambda_P t} \qquad (1.13)$$

Based on the definition of activity given in Eq. (1.7), the activity of parent nuclei P at time $t$ can be expressed as follows:

$$A_P(t) = \lambda_P N_P(t) = \lambda_P N_P(0) e^{-\lambda_P t} = A_P(0) e^{-\lambda_P t} \qquad (1.14)$$

where $A_P(0) = \lambda_P N_P(0)$ is the initial activity of the radioactive substance.

The decay law of Eq. (1.14) applies to all radioactive nuclides irrespective of their mode of decay; however, the decay constant $\lambda_P$ is different for each parent radioactive nuclide P and is the most important defining characteristic of a radioactive nuclide.

Two special time periods called half-life $(T_{1/2})_P$ and mean or average life $\tau_P$ are used to characterize a given radioactive parent substance P. The half-life $(T_{1/2})_P$ of a radioactive substance P is the time during which the number of radioactive nuclei of the substance decays to half of the initial value $N_P(0)$ present at time $t = 0$. It can also be stated that in the time of one half-life the activity $A_P(t)$ of a radioactive substance decreases to one half of its initial value $A_P(0) = \lambda_P N_P(0)$:

$$N_P\left[t = \left(T_{1/2}\right)_P\right] = \frac{1}{2} N_P(0) = N_P(0) e^{-\lambda_P \left(T_{1/2}\right)_P} \qquad (1.15)$$

And

$$A_P\left[t = \left(T_{1/2}\right)_P\right] = \frac{1}{2} A_P(0) = A_P(0) e^{-\lambda_P \left(T_{1/2}\right)_P} \qquad (1.16)$$

From Eqs (1.15) and (1.16), it is noted that $e^{-\lambda_P \left(T_{1/2}\right)_P}$ must equal 1/2, resulting in the following relationship between the decay constant $\lambda_P$ and half-life $(T_{1/2})_P$:

$$\lambda = \frac{In2}{\left(T_{1/2}\right)_P} = \frac{0.693}{\left(T_{1/2}\right)_P} \qquad (1.17)$$

Mean (average) life $\tau_P$ of a radioactive parent P is defined as the time required for the number $N_P$ of radioactive atoms or its activity $A_P$ to fall to 1/e = 0.368 (or 36.8%) of the initial number of nuclei $N_P(0)$ or of the initial activity $A_P(0)$, respectively. Thus, the following expressions describe the mean half-life:

$$N_P(t = \tau_P) = \frac{1}{e} N_P(0) = 0.368 N_P(0) = N_P(0) e^{-\lambda_P t = \tau_P} \qquad (1.18)$$

And

$$A_P[\, t = \tau_P \,] = \frac{1}{e} A_P(0) = 0.638 A_P(0) = A_P(0) e^{-\lambda_P \tau_P} \qquad (1.19)$$

From Eqs (1.18) and (1.19), it is noted that $e^{-\lambda_P \tau_P}$ must be equal to $1/e = e^{-1} = 0.368$, resulting in $\lambda_P \tau_P = 1$ and $\tau_P = 1/\lambda_P$. We now get the following relationship between mean life $\tau_P$ and half-life $(T_{1/2})_P$ using Eq. (1.17) and $\tau_P = 1/\lambda_P$:

$$\lambda = \frac{In2}{\left(T_{1/2}\right)_P} = \frac{1}{\tau_P} \qquad (1.20)$$

and

$$\tau_P = \frac{\left(T_{1/2}\right)_P}{In2} = 1.44 \left(T_{1/2}\right)_P \qquad (1.21)$$

A typical example of a radioactive decay for initial condition $A_P(t = 0) = A_P(0)$ is shown in Fig. 1.3 with a plot of parent activity $A_P(t)$ against time $t$ given in Eq. (1.14).

**Radioactive series decay**

The radioactive decay of parent P into stable daughter D, discussed in Section 1.4.1, is the simplest known radioactive decay process; however, the decay of a radioactive parent P with decay constant $\lambda_P$ into a radioactive (unstable) daughter D which in turn decays with decay constant $\lambda_D$ into a stable or unstable grand-daughter G, i.e. $P \xrightarrow{\lambda_P} D \xrightarrow{\lambda_D} G$, is much more common and results in a radioactive decay series for which the last decay product is stable.

The parent P in the decay series follows a straightforward radioactive decay described by Eq. (1.16) for the rate of change of the number of parent

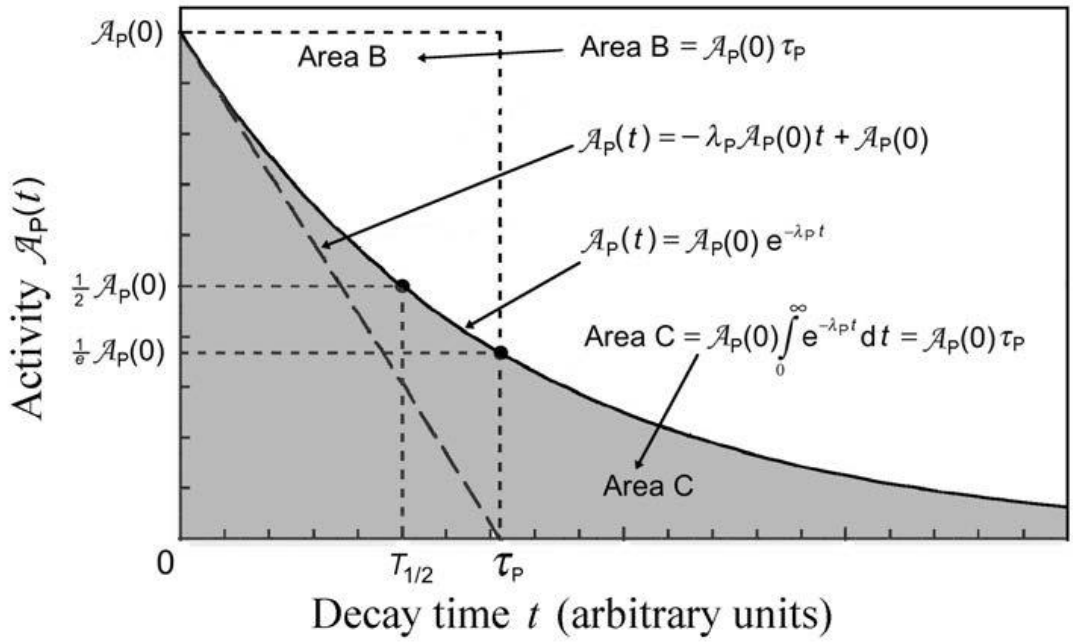



*FIG. 1.3. Activity $A_P(t)$ plotted against time t for a simple decay of a radioactive parent P into a stable or unstable daughter D. The concepts of half-life $(T_{1/2})_P$ and mean life $\tau_P$ are also illustrated. The area under the exponential decay curve from $t = 0$ to $t = \infty$ is equal to the product $A_P(0)\tau_P$ where $A_P(0)$ is the initial activity of the parent P. The slope of the tangent to the decay curve at $t = 0$ is equal to $\lambda_P A_P(0)$ and this tangent crosses the abscissa axis at $t = \tau_P$.*

nuclei $dN_P(t)/dt$. The rate of change of the number of daughter nuclei $dN_D(t)/dt$, however, is more complicated and consists of two components, one being the supply of new daughter nuclei D through the decay of P given as $\lambda_P N_P(t)$ and the other being the loss of daughter nuclei D from the decay of D to G given as $-\lambda_D N_D(t)$, resulting in the following expression for $dN_D(t)/dt$:

$$\frac{dN_{D(t)}}{dt} = \lambda_P N_P\,(t) - \lambda_D N_D\,(t) = \lambda_P N_P\,(0) e^{-\lambda_P t} - \lambda_D N_D\,(t) \qquad (1.22)$$

With the initial conditions for time $t = 0$ assuming that (i) the initial number of parent nuclei P is $N_P(t = 0) = N_P(0)$, and (ii) there are no daughter D nuclei present, i.e. $N_D(t = 0) = 0$, the solution of the differential equation in Eq. (1.22) reads as follows:

$$N_D(t) = N_P\,(0)\,\frac{\lambda_P}{\lambda_D - \lambda_P}\left[e^{-\lambda_P t} - e^{-\lambda_D t}\right] \qquad (1.23)$$

Recognizing that the activity of the daughter $A_D(t)$ is $\lambda_D N_D(t)$, the daughter activity $A_D(t)$ is written as:

$$A_D(t) = N_P(0)\frac{\lambda_D\lambda_P}{\lambda_D-\lambda_P}[e^{-\lambda_P t} - e^{-\lambda_D t}] = A_P(0)\frac{\lambda_D}{\lambda_D-\lambda_P}[e^{-\lambda_P t} - e^{-\lambda_D t}] = A_P(0)\frac{1}{1-\frac{\lambda_P}{\lambda_D}}[e^{-\lambda_P t} - e^{-\lambda_D t}] =$$
$$A_P(t)\frac{\lambda_D}{\lambda_D-\lambda_P}[e^{-(\lambda_D-\lambda_P)t}] \quad (1.24)$$

Where

$A_D(t)$ is the activity at time $t$ of the daughter nuclei equal to $\lambda_D N_D(t)$;
$A_P(0)$ is the initial activity of the parent nuclei present at time $t = 0$;
and $A_P(t)$ is the activity at time $t$ of the parent nuclei equal to $\lambda_P N_P(t)$.
While for initial conditions $A_P(t = 0) = A_P(0)$ and $A_D(t = 0) = 0$, the parent P activity $A_P(t)$ follows the exponential decay law of Eq. (1.14) shown in Fig. 1.3, the daughter D activity $A_D(t)$ starts at 0, then initially rises with time $t$, reaches a maximum at a characteristic time $t = (t_{max})_D$, and then diminishes to reach 0 at $t = \infty$. The characteristic time $(t_{max})_D$ is given as follows:

$$(t_{max})_D = \frac{In\frac{\lambda_P}{\lambda_D}}{\lambda_P-\lambda_D} \quad (1.25)$$

## Radiation quantities and units

Accurate measurement of radiation is very important in all medical uses of radiation, be it for diagnosis or treatment of disease. In diagnostic imaging procedures, image quality must be optimized, so as to obtain the best possible image with the lowest possible radiation dose to the patient to minimize the risk of morbidity. In radiotherapy, the prescribed dose must be delivered accurately and precisely to maximize the tumour control probability (TCP) and to minimize the normal tissue complication probability (NTCP). In both instances, the risk of morbidity includes acute radiation effects (radiation injury) as well as late radiation-induced effects, such as induction of cancer and genetic damage.

Several quantities and units were introduced for the purpose of quantifying radiation and the most important of these are listed in Table 1.2. Also listed are the definitions for the various quantities and the relationships between the old units and the SI units for these quantities. The definitions of radiation related physical quantities are as follows:

——*Exposure X* is related to the ability of photons to ionize air. Its unit, roentgen (R), is defined as a charge of 2.58 × 10–4 coulombs produced per kilogram of air.
——*Kerma K* (acronym for kinetic energy released in matter) is defined for indirectly ionizing radiation (photons and neutrons) as energy transferred to charged particles per unit mass of the absorber.
——*Dose* (also referred to as absorbed dose) is defined as energy absorbed per unit mass of medium. Its SI unit, gray (Gy), is defined as 1 joule of energy absorbed per kilogram of medium.
——*Equivalent dose H*T is defined as the dose multiplied by a radiation weighting factor *w*R. When different types of radiation are present, *H*T is defined as the sum of all of the individual weighted contributions. The SI unit of equivalent dose is the sievert (Sv).
——*Effective dose E* of radiation is defined as the equivalent dose *H*T multiplied by a tissue weighting factor *w*T. The SI unit of effective dose is also the sievert (Sv).
——*Activity A* of a radioactive substance is defined as the number of nuclear decays per time. Its SI unit, becquerel (Bq), corresponds to one decay per second.

## GAS FILLED DETECTORS
## Basic principles

The mode of operation of a gas filled detector depends strongly on the applied voltage. In Fig. 6.3(a), the signal amplitude is shown as a function of the voltage *V*. If upon interaction with radiation an energetic electron ploughs through the gas, the secondary electrons produced will tend to drift to the anode and the ions to the cathode (see F ig. 6.1(a)). If the voltage is relatively low, the electric

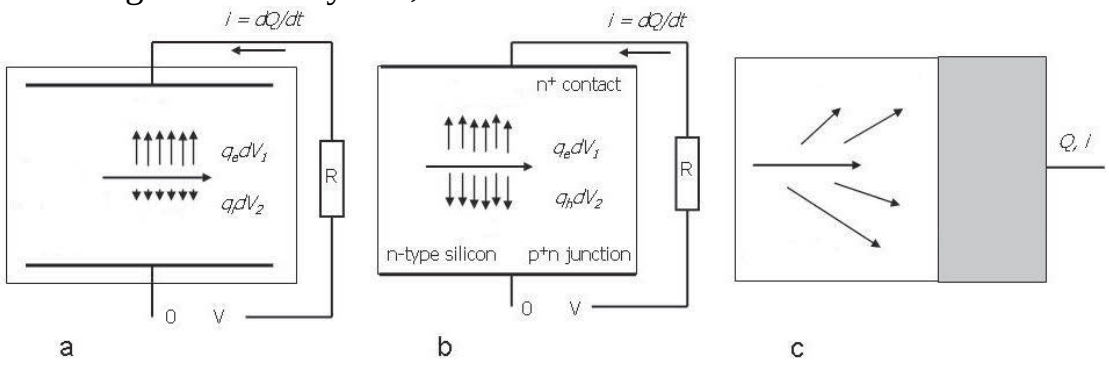



*FIG. 6.1. Principle of operation of (a) a gas filled detector, i.e. an ionization chamber; (b) a semiconductor detector, i.e. a silicon detector; and (c) a scintillation detector. The former two detectors are capacitors. The motion of charge results in an observable signal. The light of a scintillation detector is usually detected by a photomultiplier tube.*

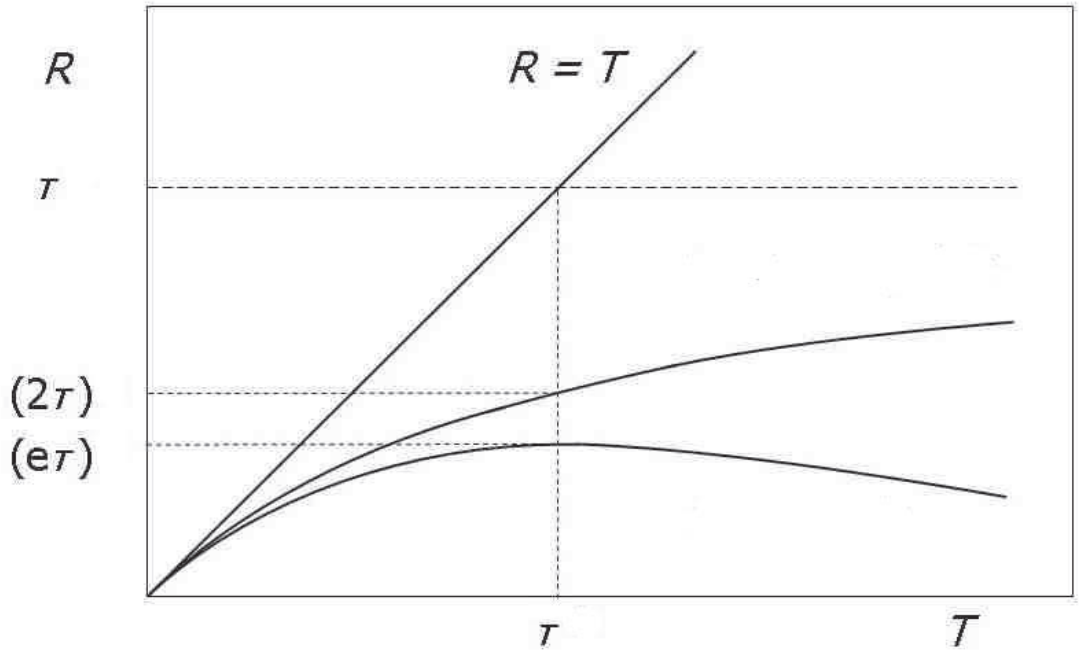



*FIG. 6.2. Counting rate R as a function of true event rate T in the absence of dead time (R = T), in the non-paralysable case and in the paralysable case.*

field $E$ is too weak to efficiently separate the negative and positive charges. A number of them will recombine. The full signal is not observed — this is in the recombination region. Increasing the voltage, more and more electrons and ions escape from recombination. The region of full ionization is now reached. For heavier charged particles and at higher rates, this will happen at a higher voltage. The signal will become constant over a wide voltage range. Typical operating voltages of an ionization chamber are in the range of 500–1000 V.

For the discussion of operation at stronger electric fields, cylindrical detector geometry with a thin anode wire in the centre and a metal cylinder as cathode (see Fig. 6.3(b)) is introduced. The electric field $E(r)$ is proportional to the applied voltage $V$ and inversely proportional to the radius $r$. At a certain voltage $V_T$, the threshold voltage, the electric field near the anode wire is so strong that a drifting electron will gain enough energy to ionize a gas atom in a collision. The proportional region is entered. If the voltage is further increased, the ionization zone will expand and an avalanche and significant gas amplification are obtained. At normal temperature and pressure, the threshold electric field $E_T \approx 106$ V/m. For parallel plate geometry with a depth of ~1 cm, this would imply that $V_T \approx 10$ kV, which is not practicable. Due to the $r^{-1}$ dependence, in the cylindrical geometry, manageable voltages can be applied for proportional operation (1–3 kV). As long as the gas gain $M$ is not too

high ($M \approx 104$), it is independent of the deposited energy. This is referred to as the proportional region and proportional counter. If the voltage is further increased, space charge effects will start to reduce the effective electric field and, consequently, affect the gain. This process will start at a lower voltage for the higher primary ionization density events. The limited proportionality region is entered. With further increasing voltage, the pulse height will eventually become independent of the deposited energy. This is the Geiger–Müller region.

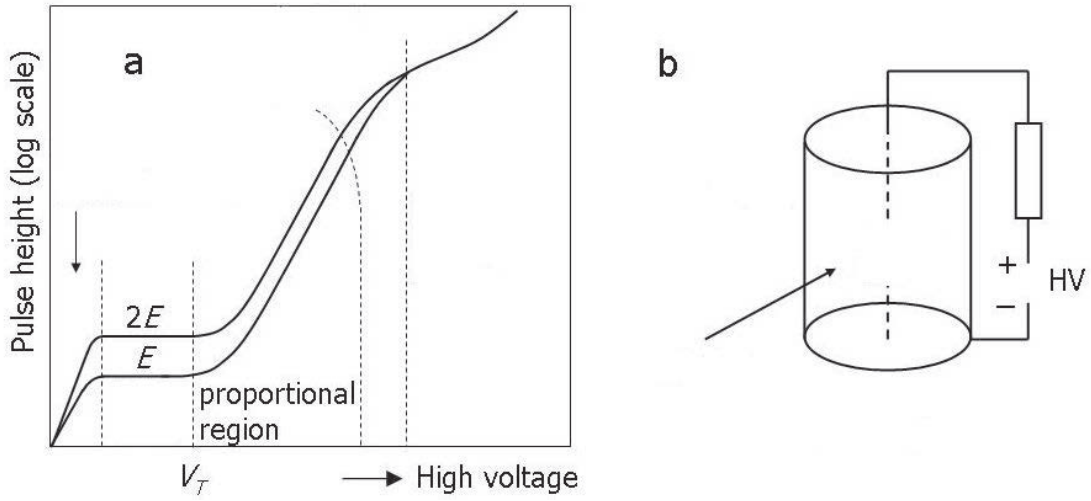



*FIG. 6.3. (a) Pulse height as a function of applied high voltage for gas filled detectors; (b) cylindrical detector geometry.*

Instead of one wire in a cylindrical geometry, many equidistant parallel anode wires at a pitch of 1–2 mm can be positioned in a plane inside a box with the walls as cathode planes. This multiwire proportional chamber (MWPC) is employed in autoradiography. The technique of photo-lithography made it possible to introduce micro-patterned detectors that operate analogously to the MWPC. Examples are the micro-strip gas chamber and the gas electron multiplier. Spatial resolutions are of the order of 0.1 mm.

## Therapy with radioactivity

By three-dimensional conformal radiotherapy (3-D CRT), we mean treatments that are based on 3-D anatomic information and use dose distributions that conform as closely as possible to the target volume in

terms of adequate dose to the tumor and minimum possible dose to normal tissue. The concept of conformal dose distribution has also been extended to include clinical objectives such as maximizing tumor control probability (TCP) and minimizing normal tissue complication probability (NTCP). Thus, the 3-D CRT technique encompasses both the physical and biologic rationales in achieving the desired clinical results.

Althoug-h 3-D CRT calls for optimal dose distribution, there are many obstacles to achieving these objectives. The most major limitation is the knowledge of the tumor extent. Despite the modern advances in imaging, the clinical target volume (CTV) is often not fully discernible. Depending on the invasive capacity of the disease, what is imaged is usually not the CTV. It may be what is called the gross tumor volume (GTV). Thus, if the CTVs drawn on the cross-sectional images do not fully include the microscopic spread of the disease, the 3-D CRT loses its meaning of being conformal. If any part of the diseased tissue is missed or seriously underdosed, it will inevitably result in failure despite all the care and effort expended in treatment planning, treatment delivery, and quality assurance. From the TCP point of view, accuracy in localization of CTV is more critical in 3-D CRT than in techniques that use generously wide fields and simpler beam arrangements to compensate for the uncertainty in tumor localization.

In addition to the difficulties in the assessment and localization of CTV, there are other potential errors that must be considered before planning 3-D CRT. Patient motion, including that of tumor volume, critical organs and external fiducial marks during imaging, simulation, and treatment, can give rise to systematic as well as random errors that must be accounted for when designing the planning target volume (PTV). If sufficient margins have been allowed for in the localization of PTV, the beam apertures are then shaped to conform and adequately cover the PTV (e.g., within 95% to 105% isodose surface relative to prescribed dose). In the design of conformal fields to adequately treat the PTV, consideration must be given to the cross-beam profile, penumbra, and lateral radiation transport as a function of depth, radial distance, and tissue density. Therefore, sufficient margins must be given between the PTV outline and the field boundary to ensure adequate dose to PTV at every treatment session.

Even if the fields have been optimally designed, biologic response of the tumor and the normal tissues needs to be considered in achieving the goals of 3-D CRT. In other words, the optimization of a treatment plan has to be evaluated not only in terms of dose distribution (e.g., dose volume histograms) but also in terms of dose-response characteristics

of the given disease and the irradiated normal tissues. Various models involving TCP and NTCP have been proposed, but the clinical data to validate these models are scarce.

Until more reliable data are available, caution is needed in using these concepts to evaluate treatment plans. This is especially important in considering dose-escalation schemes that invariably test the limits of normal tissue tolerance within or in proximity to the PW.

Notwithstanding the formidable obstacles in defining and outlining the true extent of the disease, the clinician must follow an analytic plan recommended by the International Commission on Radiation Units and Measurements (ICRU) (1). Various target volumes (GW, CW, PW, etc.) should be carefully designed considering the inherent limitations or uncertainties at each step of the process. The final PW should be based not only on the given imaging data and other diagnostic studies but also the clinical experience that has been obtained in the management of that disease. Tightening of field margins around image-based GW, with little attention to occult disease, patient motion, or technical limitations of dose delivery, is a misuse of 3-D CRT concept that must be avoided at all cost. It should be recognized that 3-D CRT is not a new modality of treatment, nor is it synonymous with better results than successful and well-tested conventional radiation therapy. Its superiority rests entirely on how accurate the PW is and how much better the dose distribution is. So, instead of calling it a new modality, it should be considered as a superior tool for treatment planning with a potential of achieving better results.

**Radiation doses in nuclear medicine**

Radiation doses of the order of several grays may lead to cell loss. Cells
are generally regarded as having been ‘killed’ by radiation if they have lost reproductive integrity, even if they have physically survived. Loss of reproductive integrity can occur by apoptosis, necrosis, mitotic catastrophe or by induced senescence. Although all but the last of these mechanisms ultimately results in physical loss of the cell, this may take a significant time to occur.

Apoptosis or programmed cell death can occur naturally or result from insult to the cell environment. Apoptosis occurs in particular cell types after low doses of irradiation, e.g. lymphocytes, serous salivary gland cells, and certain cells in the stem cell zone in testis and intestinal crypts.

Necrosis is a form of cell death associated with loss of cellular membrane activity. Cellular necrosis generally occurs after high radiation doses.

Reproductive cell death is a result of mitotic catastrophe (cells attempt to divide without proper repair of DNA damage) which can occur in the first few cell divisions after irradiation, and it occurs with increasing frequency after increasing doses.

Ionizing radiation may also lead to senescence. Senescent cells are metabolically active but have lost the ability to divide.

# Physics of the skeleton

## Bones

Bone has at least six functions in the body:

1. Support.
2. Locomotion.
3. Protection of various organs.
4. Storage of chemicals.
5. Nourishment.
6. Sound transmission ( in the middle ear ).

## Composition of bone

The detailed chemical composition of bone is given in table 1. Note the large percentage of calcium ( Ca ) in bone. Since calcium has a much heavier nucleus than most elements of the body, it absorbs x-rays much better than the surrounding soft tissue. This is the reason x-rays show bones so well.

Bone consists of two quite different materials plus water:

1. Collagen is the major organic fraction, which is about 40% of the weight of solid bone and 60% of its volume.
2. Bone mineral is the so-called inorganic component of bone, which is about 60% of the weight of the bone 40% of its volume.

**Table 1 Composition of Compact Bone**

| Element | Compact Bone, Femur (%) |
|---|---|
| H | 3.4 |
| C | 15.5 |
| N | 4.0 |
| O | 44.0 |
| Mg | 0.2 |
| P | 10.2 |
| S | 0.3 |
| Ca | 22.2 |
| Miscellaneous | 0.2 |

## Bone remodeling

Continuous process of destroying old bone and building new bone by specialized bone cells.

## Trabecular bone (Fig. 1 ):

1. It made up of thin thread.
2. It predominately found in the ends of the long bones.
3. It is considerably weak due to the reduced amount of bone in a given volume.

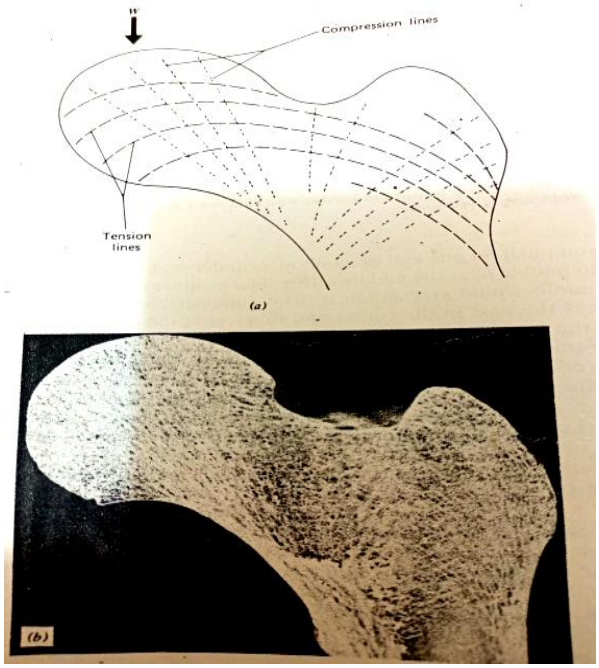



**Figure 1**

## Compact bone ( Fig. 2):

1. It made up of thick plates.
2. It  predominately found in the central shaft of the bone.
3. It is considerably strong due to the large amount of bone in a given volume.

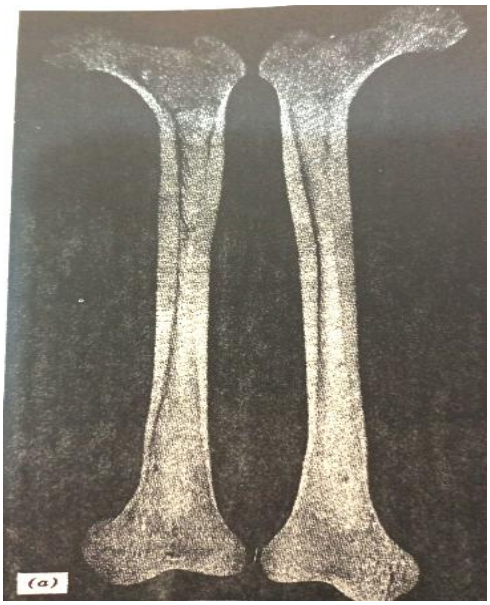



Figure 2

## Stress-strain curve

All materials change in length when placed under tension or compression. When a sample of fresh bone is placed in a special instrument for measuring the elongation under tension a curve similar to that in Fig. 3 is obtained. The strain ΔL/L increases linearly at first, indicating that it is proportional to the stress ( F/A ) – Hooke's law. As the force increases the length increases more rapidly, and the bone breaks at stress of about 120 $N/mm^2$ . The ratio of stress to strain in the initial linear portion is Young's modulus Y. That is,

$$Y = \frac{LF}{A\Delta L} \dots\dots\dots\dots\dots (1)$$

Young's moduli for bone and a few common structural materials are given in table 2. It is usually of more interest to calculate the change in length ΔL for a given force F. Equation 1 can be rewritten as

$$\Delta L = \frac{LF}{AY} \dots\dots\dots\dots\dots (2)$$

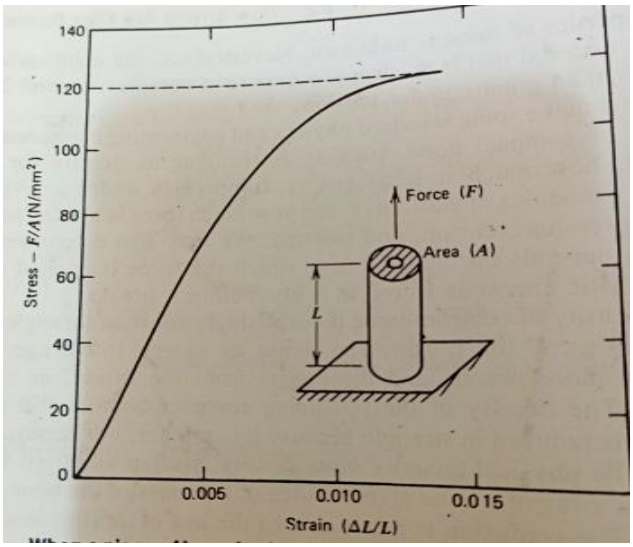



Figure 3

**Table 2 Strengths of Bone and Other Common Materials**

| Material | Compressive Breaking Stress ($N/mm^2$) | Tensile Breaking Stress ($N/mm^2$) | Young's Modulus of Elasticity ($\times 10^2$ $N/mm^2$) |
|---|---|---|---|
| Hard steel | 552 | 827 | 2070 |
| Rubber | — | 2.1 | 0.010 |
| Granite | 145 | 4.8 | 517 |
| Concrete | 21 | 2.1 | 165 |
| Oak | 59 | 117 | 110 |
| Porcelain | 552 | 55 | — |
| Compact bone | 170 | 120 | 179 |
| Trabecular bone | 2.2 | — | 0.76 |

Equations 1 and 2 are valid for both tension and compression ( see example 1 ).

**Example 1**

Assume a leg has a 1.2 m shaft of bone with an average cross-sectional area of 3 $cm^2$. What is the amount of shortening when all of the body weight of 700 N is supported on this leg?

$$\Delta L = \frac{LF}{AY} = \frac{(1.2m)(7 \times 10^2 N)}{(3 \times 10^{-4} m^2)(1.8 \times 10^{10}\ N/m^2)} = 1.5 \times 10^{-4} m = 0.15\ mm$$

## Bone joints

There are two major diseases that affect the joints-rheumatoid arthritis, which results in overproduction of synovial fluid in the joint and commonly causes swollen joints, and osteoarthrosis, a disease of the joint itself.

The main components of a joint are shown in Fig. 4. The synovial membrane encases the joint and retains the lubricating synovial fluid. The surfaces of the joint are articular cartilage, a smooth, somewhat rubbery material that is attached to solid bone. A disease that involves the synovial fluid, such as rheumatoid arthritis, quickly affects the joint itself.

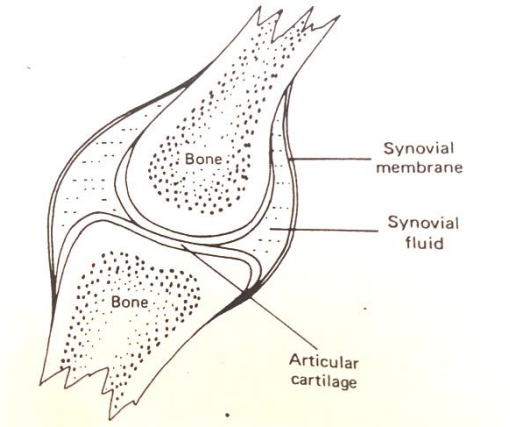



Figure 4

The lubricating properties of a fluid depend on its viscosity; thin oil is less viscous and a better lubricant than thick oil. The viscosity of synovial fluid decreases under the large shear stresses found in the joint. The good lubricating properties of synovial fluid are thought to be due to the presence of hyaluronic acid and mucopolysaccharides ( molecular weight, ~ 500,000 ) that deform under load.

The coefficient of frication of bone joints is difficult to measure under the usual laboratory conditions. Little, Freeman, and Swanson described the arrangement shown in Fig. 5. A normal hip joint from a fresh cadaver was mounted upside down with heavy weights pressing the head of the femur into its socket. The weight on the joint could be varied to study the effects of different loads. The whole unit acted like a pendulum with the joint serving as the pivot. From the rate of decrease of the amplitude with time, the coefficient of frication

was calculated. The coefficient of friction was found to be independent of the load from 89 to 890 N and independent of the magnitude of the oscillations. It was concluded that fat in the cartilage helps to reduce the coefficient of friction. For all healthy joints studied, the coefficient of friction was found to be less than 0.01, much less than that of a steel blade on ice-0.03.

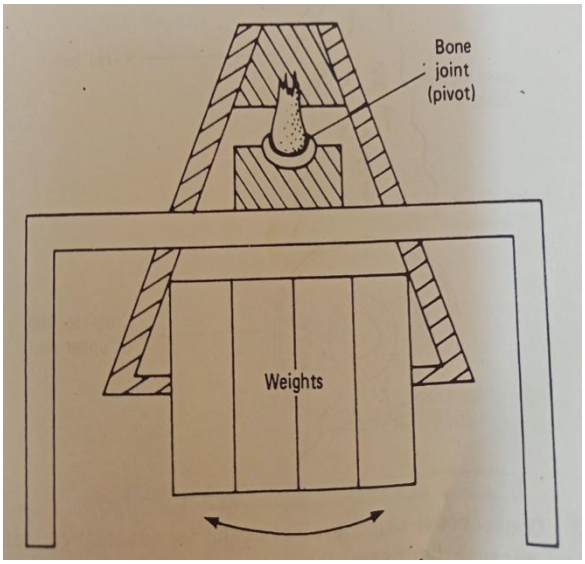



Figure 5

# Pressure

## Definition

Pressure is defined as the force per unit area in a gas or a liquid. For a solid the quantity force per unit area is referred to as stress.

## Unit of pressure

In the metric system pressure is measured in dynes per square centimeter or newtons per square meter; the SI unit for the latter is the pascal (Pa). Table 1 lists some of the common units used to measure pressure and gives atmospheric pressure in each system.

Table 1 Some of the units used to measure pressure

| | Atmospheres | $N/m^2$ | $cm\ H_2O$ | mm Hg | $lb/in.^2$ (psi) |
|---|---|---|---|---|---|
| 1 atmosphere | 1 | $1.01 \times 10^5$ | 1033 | 760 | 14.7 |
| 1 $N/m^2$ | $0.987 \times 10^{-5}$ | 1 | 0.0102 | 0.0075 | $0.145 \times 10^{-3}$ |
| 1 cm $H_2O$ | $9.68 \times 10^{-4}$ | 98.1 | 1 | 0.735 | 0.014 |
| 1 mm Hg | 0.00132 | 133 | 1.36 | 1 | 0.0193 |
| 1 $lb/in.^2$ (psi) | 0.0680 | 6895 | 70.3 | 51.7 | 1 |

## Pressure calculation

The pressure P under a column of liquid can be calculated from

$$P = \rho g h$$

Where ρ is the density of the liquid, g is the acceleration due to gravity, and h is the height of the column.

## Absolute and gauge pressure

Since we live in a sea of air with a pressure of 1 atm, it is easier to measure pressure relative to atmospheric pressure than to measure true, or absolute pressure. For example, if the pressure in a bicycle tire is 60 $lb/in.^2$, the absolute pressure is 60+14.7, or nearly 75 $lb/in.^2$ The 60 $lb/in.^2$ is the gauge pressure.

## Negative pressure

There are a number of places in the body where the pressures are lower than atmospheric, or negative. For example, when we breathe in (inspire) the pressure in the lungs must be somewhat lower than atmospheric pressure or the air would not flow in. The lung pressure during inspiration is typically a few centimeters of water negative. When a person drinks through a straw the pressure in his mouth must be negative by an amount equal to the height of his mouth above the level of the liquid he is drinking.

## Measurement of pressure in the body

The classical method of measuring pressure is to determine the height of a column of liquid that produces a pressure equal to the pressure being measured. An instrument that measures pressure by this method is called a manometer. A common type of manometer is a **U**-shaped tube containing a fluid that is connected to the pressure to be measured (Fig. 1). The levels in the arms change until the difference in the levels is equal to the pressure. This type of manometer can measure both positive and negative pressure. The fluid used is usually mercury, but water or other low density fluids can be used when the pressure to be measured is relatively small.

The most common clinical instrument used in measuring pressure is the sphygmomanometer, which measures blood pressure. Two types of pressure gauges are used in sphygmomanometers. In a mercury manometer type the pressure is indicated by the height of a column of mercury inside a glass tube. In an aneroid type the pressure changes the shape of a sealed flexible container, which causes a needle to move on a dial.

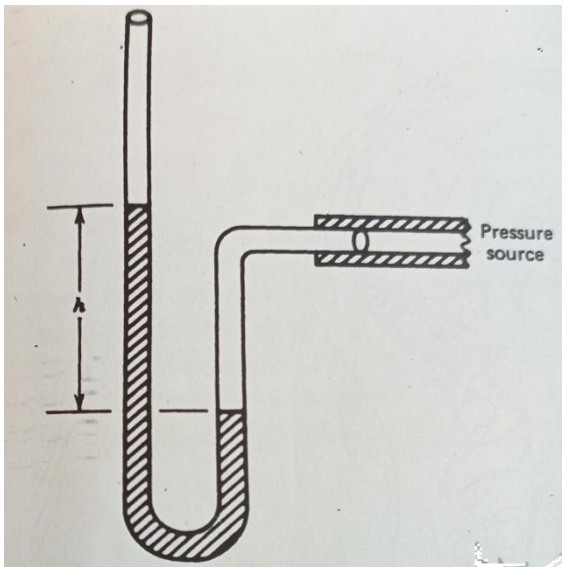



Figure 1

Some parts of the body can act like crude pressure indicators. For example, a person going up or down in an elevator or an airplane is often aware of the change in atmospheric pressure on the ears. When one swallows the pressure in the middle ear equalizes to the outside pressure and the eardrums " pop." It is necessary for the ears to be very sensitive to pressure since pressure changes in an ordinary sound wave are extremely small. Another qualitative pressure indicator is the size of the veins on the back of the hand. As a hand is raised slightly above the level of the heart these veins become smaller due to the lower venous blood pressure.

# Sound in medicine

## General properties of sound

A sound wave is a mechanical disturbance in a gas, liquid, or solid that travels outward from the source with some definite velocity. We can use a loudspeaker vibrating back and forth in air at a frequency $f$ to demonstrate the behavior of sound. The vibrations cause local increases and decreases in pressure relative to atmospheric pressure ( Fig. 1 ). These pressure increases, called compressions, and decreases, called rarefactions, spread outward as a longitudinal wave, that is, a wave in which the pressure changes occur in the same direction the wave travels. The compressions and rarefactions can also be described by density changes and by displacement of the atoms and molecules from their equilibrium positions.

The relationship between the frequency of vibration $f$ of the sound wave the wavelength λ, and the velocity ν of the sound wave is

$$\nu = \lambda f$$

For example, for a sound wave with a frequency of 1000 Hz, ν=344 m/sec in air at 20 °C and λ= 0.344 m.

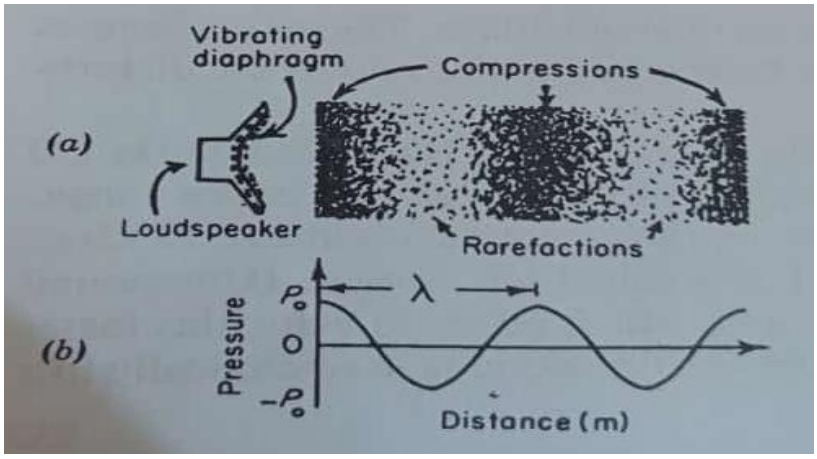



Figure 1

Table1 Values of ρ, ν, and Z for various substances at clinical ultrasound frequencies

| | $\rho$ (kg/m$^3$) | $\nu$ (m/sec) | $Z$ (kg/m$^2$ · sec) |
|---|---|---|---|
| Air | 1.29 | $3.31 \times 10^2$ | 430 |
| Water | $1.00 \times 10^3$ | $14.8 \times 10^2$ | $1.48 \times 10^6$ |
| Brain | $1.02 \times 10^3$ | $15.3 \times 10^2$ | $1.56 \times 10^6$ |
| Muscle | $1.04 \times 10^3$ | $15.8 \times 10^2$ | $1.64 \times 10^6$ |
| Fat | $0.92 \times 10^3$ | $14.5 \times 10^2$ | $1.33 \times 10^6$ |
| Bone | $1.9 \times 10^3$ | $40.4 \times 10^2$ | $7.68 \times 10^6$ |

Energy is carried by the wave as potential and kinetic energy. The intensity I of a sound wave is the energy passing through 1 m$^2$/sec, or watts per square meter. For a plane wave I is given by

$$I = \frac{1}{2}\rho\nu A^2 (2\pi f)^2 = \frac{1}{2} Z(A\omega)^2 \ldots\ldots\ldots\ldots (1)$$

Where ρ is the density of the medium; ν is the velocity of sound; $f$ is the frequency; ω is the angular frequency, which equals $2\pi f$ ; A is the maximum displacement amplitude of the atoms or molecules from the equilibrium position; and Z, which equals ρν, is the acoustic impedance. Some typical values of ρ, ν , and Z are given in table 1. The intensity can also be expressed as

$$I = \frac{P_o^2}{2Z} \ldots\ldots\ldots\ldots\ldots (2)$$

Where $P_O$ is the maximum change in pressure.

When a sound wave hits the body, part of the wave is reflected and part is transmitted into the body ( Fig. 2 ). The ratio of the reflected pressure amplitude R to the incident pressure amplitude $A_O$ depends on the acoustic impedances of the two media, $Z_1$ and $Z_2$. The relationship is

$$\frac{R}{A_o} = \frac{Z_2 - Z_1}{Z_1 + Z_2} \ldots\ldots\ldots\ldots (3)$$

For a sound wave in air hitting the body, $Z_1$ is the acoustic impedance of air and $Z_2$ is the acoustic impedance of tissue. Note that if $Z_1$=$Z_2$, there is no reflected wave and transmission to the second medium is complete. Also, if $Z_2$< $Z_1$, the sign change indicates a phase change of the reflected wave.

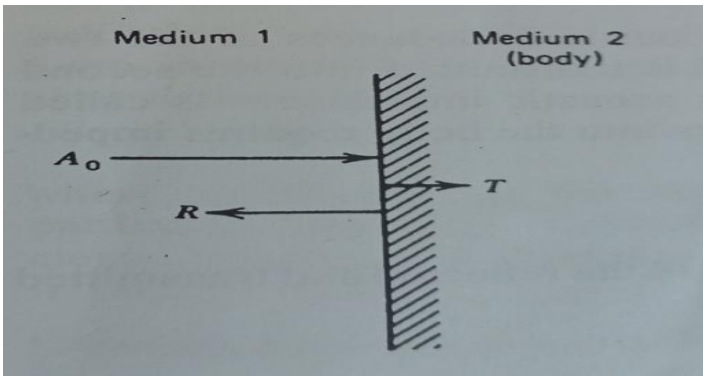



Figure 2

The ratio of the transmitted pressure amplitude T to the incident wave amplitude $A_o$ is

$$\frac{T}{A_o} = \frac{2Z_2}{Z_1 + Z_2} \quad \ldots\ldots\ldots\ldots\ldots (4)$$

In our discussion of the reflection of a sound wave we assumed that the wave was perpendicular to the surface. Thus the transmitted wave went straight in and the reflected wave went straight back. How do the reflected and transmitted sound waves behave when a wave hits at an angle $\theta_i$ to a boundary between two media ( Fig. 3 )?

The geometric laws involving the reflection and refraction ( bending) are the same as for light. This means that θ incident = θ reflected, or $\theta_i = \theta_r$. The angle of the refracted sound wave $\theta_2$ is determined by the velocities of sound in the two media $v_1$ and $v_2$ from the equation

$$\frac{sin\theta_i}{v_1} = \frac{sin\theta_2}{v_2}$$

Because sound can be refracted, acoustic lenses can be constructed to focus sound waves.

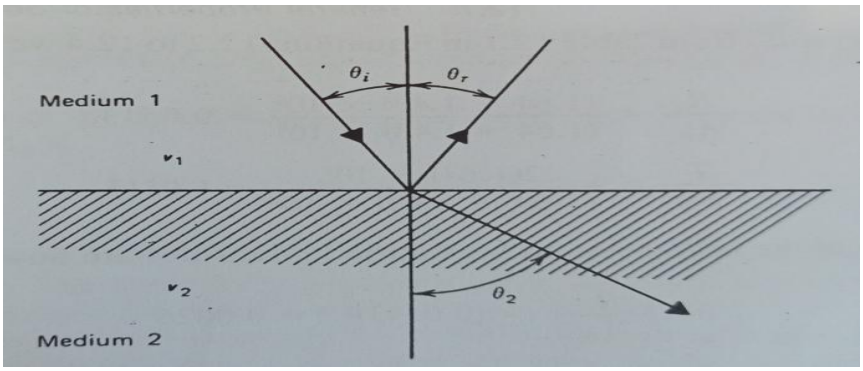



Figure 3

When s sound wave passes through tissue, there is some loss of energy due to frictional effects. The absorption of energy in the tissue causes a reduction in the amplitude of the sound wave. The amplitude A at a depth x cm in a medium is related to the initial amplitude $A_o$ (x=0) by the exponential equation

$$A = A_o e^{-\alpha x}$$

Where α, in $cm^{-1}$ , is the absorption coefficient for the medium at a particular frequency. Table 2 gives some typical absorption coefficients.

Table 2 Absorption coefficients and half-value thicknesses for various substances.

| Material | Frequency (MHz) | $\alpha$ ($cm^{-1}$) | Half-Value Thickness (cm)[a] |
|---|---|---|---|
| Muscle | 1 | 0.13 | 2.7 |
| Fat | 0.8 | 0.05 | 6.9 |
| Brain (ave) | 1 | 0.11 | 3.2 |
| Bone (human skull) | 0.6 | 0.4 | 0.95 |
| | 0.8 | 0.9 | 0.34 |
| | 1.2 | 1.7 | 0.21 |
| | 1.6 | 3.2 | 0.11 |
| | 1.8 | 4.2 | 0.08 |
| | 2.25 | 5.3 | 0.06 |
| | 3.5 | 7.8 | 0.045 |
| Water | 1 | $2.5 \times 10^{-4}$ | $1.4 \times 10^{3}$ |

Since the intensity is proportional to the square of the amplitude, its dependence with depth is

$$I = I_o e^{-2\alpha x} \ldots\ldots\ldots\ldots\ldots (5)$$

Where $I_0$ is the incident intensity at x=0 and I is the intensity at a depth x in the absorber. Since the absorption coefficient in equation 5 is 2α, the intensity decreases more rapidly than the amplitude with depth.

The half-value thickness (HVT) is the tissue thickness needed to decrease $I_0$ to $I_0/2$. Table 2 gives typical HVTs for different tissues. Note the high absorption in the human skull and that the absorption increases as the frequency of the sound increases. This increasing absorption with frequency also occurs for other body tissues and limits the maximum frequencies that can be used clinically (Fig. 4).

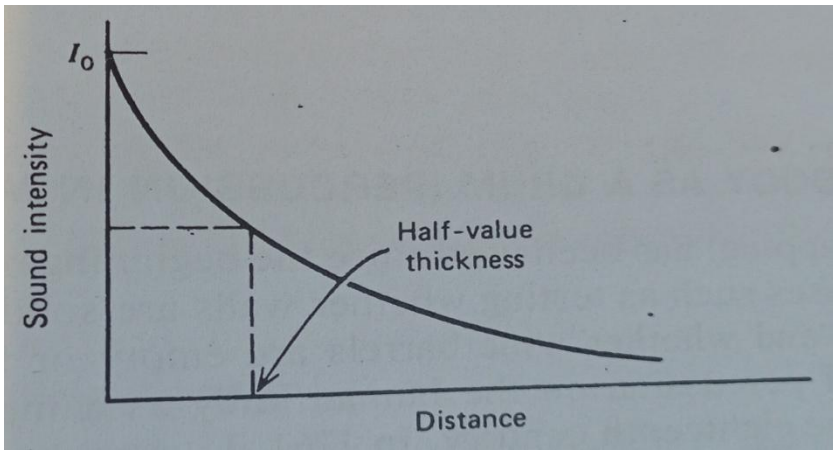



Figure 4

In addition to the absorption of sound, the spreading out, or divergence, of sound causes the intensity to decrease. If the sound is from a small source (point source) the divergence causes the intensity to decrease according to the inverse square law. That is, I is proportional to $1/r^2$ where r is the distance from the source to the measuring point.

**The stethoscope**

The main parts of a modern stethoscope are bell, which is either open or closed by a thin diaphragm, the tubing, and the earpieces (Fig. 5) .

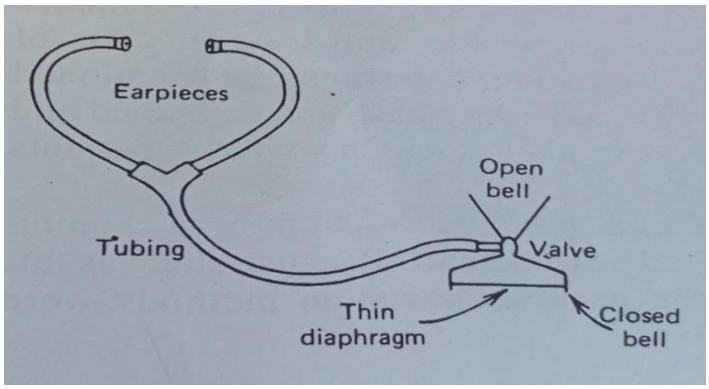



Figure 5

The open bell is an impedance matcher between the skin and the air and accumulates sounds from the contacted area. The skin under the open bell behaves like a diaphragm. The skin diaphragm has a natural resonant frequency at which it most effectively transmits sounds; the factors controlling the resonant frequency are similar to those controlling the frequency of a stretched vibrating wire. The tighter the skin in pulled, the higher its resonant frequency. The larger the bell diameter, the lower the skin's resonant frequency. Thus it is possible to

enhance the sound range of interest by changing the bell size and vary the pressure of the bell against the skin and thus the skin tension. A low-frequency heart murmur will appear to go away if the stethoscope is pressed hard against the skin!

A closed bell is merely a bell with a diaphragm of known resonant frequency, usually high, that tunes out low-frequency sounds. Its resonant frequency is controlled by the same factors that control the frequency of the open bell pressed against the skin. The closed-bell stethoscope is primarily used for listening to lung sounds, which are of higher frequency than heart sounds. Figure 6 shows the typical frequency ranges of heart and lung sounds.

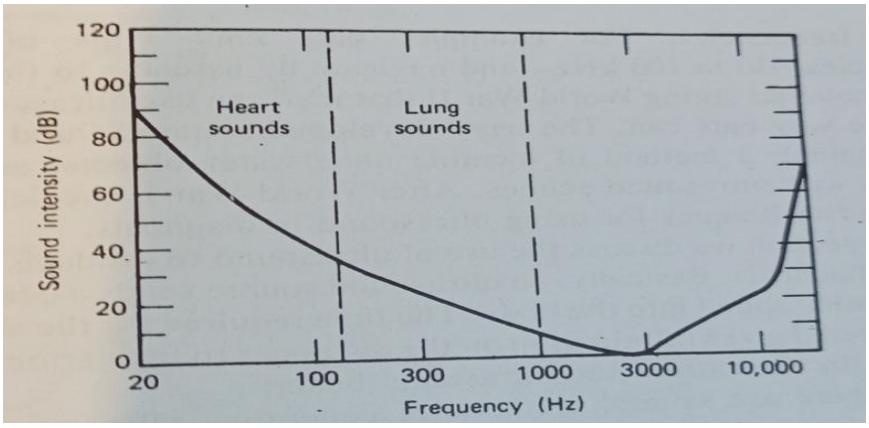



Figure 6

The volume of the tubes should also be small, and there should be little frictional loss of sound to the walls of the tubes. The small volume restriction suggests short, small diameter tubes, while the low-friction restriction suggests large diameter tubes. If the diameter of the tube is too small, frictional losses occur, and if it is too large, the moving air volume is too great; in both cases the efficiency is reduced. Below about 100 Hz tube length does not greatly affect the efficiency, but above this frequency the efficiency decreases as the tube is lengthened. At 200Hz 15dB is lost in changing from a tube 7.5 cm long to a tube 66 cm long. A compromise is a tube with a length of about 25 cm and a diameter of 0.3 cm.

The earpieces should fit snugly in the ear because air leaks reduce the sounds heard. The lower the frequency, the more significant the leak. Leaks also allow background noise to enter the ear. The earpieces are usually designed to follow the slightly forward slant of the ear canals.

## Mechanism of hearing

The sense of hearing involves:

1. The mechanical system that stimulates the hair cells in the cochlea.
2. The sensors that produce the action potentials in the auditory nerves.
3. The auditory cortex, the part of the brain that decodes and interprets the signals from the auditory nerves ( Fig. 7).

Deafness or hearing loss results if any of these parts malfunctions.

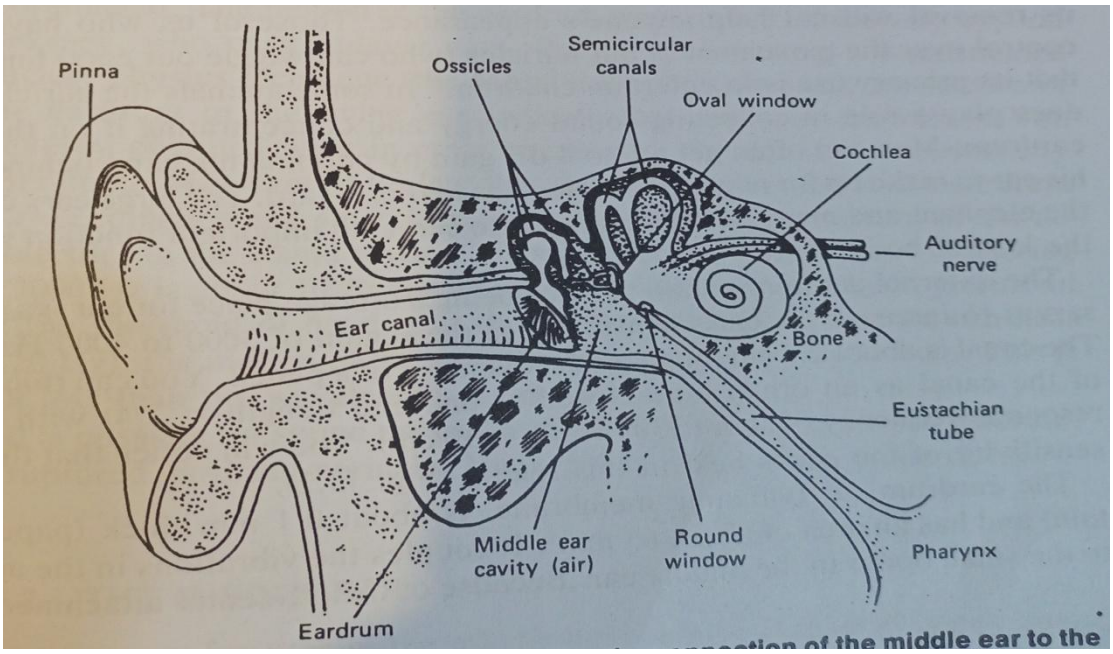



Figure 7

# Terminology of Medical Physics

## Terminology, Modeling, and Measurement

### 1- Terminology

The term medical physics refers to **two** major areas: -

**1.** The applications of physics to the functions of the human body in health and disease.

**2.** The applications of physics in the practice of medicine.

**The first** of these could be called the physics of physiology; **the second** includes such things as the physics of the stethoscope, the tapping of the chest (percussion), and the medical applications of lasers, ultrasound, radiation and so forth.

The word **physical** appears in a number of medical contexts. Only a generation ago in England a professor of physics was actually a professor of medicine.

The branch of medicine referred to as **physical medicine** deals with the diagnosis and treatment of disease and injury by means of physical agents such as manipulation, massage, exercise, heat, and water.

**Physical therapy** is the treatment of disease or bodily weakness by physical means such as massage and gymnastics rather than by drugs.

**The field of medical physics has several subdivisions: -**

**1.** Most medical physicists in the United States work in the field of **radiological physics**. This involves the applications of physics to radiological problems and includes the use of radiation in the diagnosis and treatment of disease as well as the use of radionuclides in medicine (nuclear medicine).

**2.** Another major subdivision of medical physics involves **radiation protection** of patients, workers, and the general public. In the United States this field is often called **health physics**. Health physics also includes radiation protection outside of the hospital such as around nuclear power plants and in industry.

**3.** Very often an applied field of physics ( included design and instrumentation) is called **engineering**. Thus, medical physics could be called **medical engineering**.

**4.** The word **medical** is sometimes replaced with the word **clinical** if the job is closely connected with patient problems in hospitals, i.e., clinical engineering or clinical physics.

## 2- Modeling

Even though physicists believe that the physical world obeys the laws of physics, they are also aware that the mathematical descriptions of some physical situations are too complex to permit solutions.

If you tore a small corner off this page and let it fall to the floor, it would go through various gyrations. Its path would be determined by the laws of physics, but it would be almost impossible to write the equation describing this path. Physicists would agree that the force of gravity would cause it to go in the general direction of the floor if some other force did not interfere. Air currents and static electricity would affect its path.

In trying to understand the physical aspects of the body, we often resort to analogies; physicists often teach and think by analogy. Keep in mind that analogies are never perfect.

In many ways the eye is analogous to a camera; however, the analogy is poor when the film, which must be developed and replaced, is compared to the retina, the light detector of the eye.

Some models involve physical phenomena that appear to be completely unrelated to the subject being studied.

A model in which the flow of blood is represented by the flow of electricity is often used in the study of the body's circulatory system. Also, all analogies have their limitations.

Blood is made up of red blood cells and plasma, and the percentage of the blood occupied by the red blood cells (the hematocrit) changes as the blood flows toward the extremities. This phenomenon is difficult to simulate with the electrical model.

Other models are mathematical; equations are mathematical models that can be used to describe and predict the physical behavior of some systems. In the everyday world of physics we have many such equations. Some are of such general use that they are referred to as laws.

## 3- **Measurement**

One of the main characteristics of science is its ability to reproducibly measure quantities of interest. The growth of science is closely related to the growth of the ability to measure. In the practice of medicine, early efforts to measure quantities of clinical interest were often scorned as detracting from the skill of the physician.

Even though body temperature and pulse rate could be measured during the seventeenth century, these measurements were not routinely made until the nineteenth century. In this century there has been a steady growth of science in medicine as the number and accuracy of quantitative measurements used in clinical practice have increased.

The following figure illustrates a few of the common measurements used in the practice of medicine. Some of these measurements are more reproducible than others.

**For Example: -**

An x-ray gives only qualitative information about the inside of the body; a repeat x-ray taken with a different machine may look quite different to the ordinary observer.

There are many other physical measurements involving the body and time. We can divide them into two groups: -

**1.** Measurements of the repetitive processes usually involve the number of repetitions per second, minute, hour, and so forth, such as the pulse rate which is about 70/min and the breathing rate which is about 15/min.

**2.** Measurements of nonrepetitive processes, such as how long it takes the kidneys to remove a foreign substance from the blood. Nonrepetitive time processes in the body range from the action potential of a nerve cell (1msec) to the lifespan of an individual.

**In science accuracy and precision have different meanings: -**

**Accuracy**

It refers to how close a given measurement is to an accepted standard.

**For Example: -**

A person's height measured as 1.765 m may be accurate to 0.003 m (3 mm) compared to standard meter.

**Precision**

It refers to the reproducibility of a measurement and is not necessarily related to the accuracy of the measurement.

**For Example: -**

An ill person measured her temperature ten times in a row and got the following values in degrees Celsius: 36.1, 36.0, 36.1, 36.2, 36.4, 36.0, 36.3, 36.3, 36.4, and 36.2. The precision was fairly good, with a variation of 0.2°C from the average value of 36.2°C.

It is an accepted fact in science that the process of measurement may significantly alter the quantity being measured. This is especially true in medicine.

**For example:**

The process of measuring the blood pressure may introduce errors (uncertainties). Although the data are scarce, it is generally believed that when an attractive woman is performing the measurement, the blood pressure of a young man will increase. Similarly, a handsome man may affect the blood pressure measurement of a female patient.

**When the physician decides if the patient is ill or not?**

After he or she has reviewed a patient's: -

**1.** Medical history.

**2.** The findings of the physical examination.

**3.** The results of clinical laboratory measurements.

It is not surprising that sometimes wrong decisions are made. These wrong decisions are of two types: -

**1.** False Positives.

**2.** False Negatives.

A **false positive** error occurs when a patient is diagnosed to have a particular disease when he or she does not have it.

A **false negative** error occurs when a patient is diagnosed to be free of a particular disease when he or she does have it.

**Note: -** In some situations a diagnostic error can have a great impact on a patient's life.

**For Example: -**

A young woman was thought to have a rheumatic heart condition and spent several years in complete bed rest before it was discovered that a false positive diagnosis had been made-she really had arthritis.

In the early stages of many types of cancer it is easy to make a false negative diagnostic error because the tumor is small. Since the probability of cure depends on early detection of the cancer, a false negative diagnosis can greatly reduce the patient's chance of survival.

**Diagnostic errors (false positives and false negatives) can be reduced by: -**

**1.** Research into the causes of misleading laboratory test values.

**2.** Development of new clinical tests and better instrumentation.

**Errors or uncertainties from measurements can be reduced by: -**

**1.** Using care in taking the measurement.

**2.** Repeating measurements.

**3.** Using reliable instruments.

**4.** Properly calibrating the instruments.

# Ultrasound

## A-scan

To obtain diagnostic information about the depth of structures in the body, we send pulses of ultrasound into the body and measure the time required to receive the reflected sound (echoes) from the various surfaces in it. This procedure is called the A scan method of ultrasound diagnosis. Pulses for A scan work are typically a few microseconds long. They are usually emitted at 400 - 1000 pulses/sec.

The A scan method is illustrated schematically in fig. 1 . In Fig. 1a, a transducer T sends a pulse of ultrasound through a beaker of water of diameter d. The sound is reflected from the other side of the beaker and returns to the transducer, which also acts as a receiver. The detected echo is converted to an electrical signal and is displayed as the vertical deflection R on the cathode ray tube (CRT) of an oscilloscope (Fig. 1a' ). Since the echo has been attenuated by the water, R is smaller in amplitude than the initial pulse shown on the oscilloscope at 0. The time required for the pulse to travel from the transducer to the far side and return to the transducer is indicated on the horizontal scale of the oscilloscope. This time can easily be converted to distance by using the known velocity of sound in water ( Table 1) to calibrate the scale.

Table1 Values of ρ, ν, and Z for various substances at clinical ultrasound frequencies

| | $\rho$ (kg/m$^3$) | $\nu$ (m/sec) | $Z$ (kg/m$^2$ · sec) |
|---|---|---|---|
| Air | 1.29 | $3.31 \times 10^2$ | 430 |
| Water | $1.00 \times 10^3$ | $14.8 \times 10^2$ | $1.48 \times 10^6$ |
| Brain | $1.02 \times 10^3$ | $15.3 \times 10^2$ | $1.56 \times 10^6$ |
| Muscle | $1.04 \times 10^3$ | $15.8 \times 10^2$ | $1.64 \times 10^6$ |
| Fat | $0.92 \times 10^3$ | $14.5 \times 10^2$ | $1.33 \times 10^6$ |
| Bone | $1.9 \times 10^3$ | $40.4 \times 10^2$ | $7.68 \times 10^6$ |

An object in the beaker can be located with ultrasound. In Fig. 1b a surface S at a distance $d_1$ produces an additional echo, which is displayed on the oscilloscope as S at the position $d_1$ (Fig. 1b'). Note that the echo R is now smaller. When the surface vibrates (Fig. 1c), the position of the echo on the oscilloscope also moves (Fig. 1c').

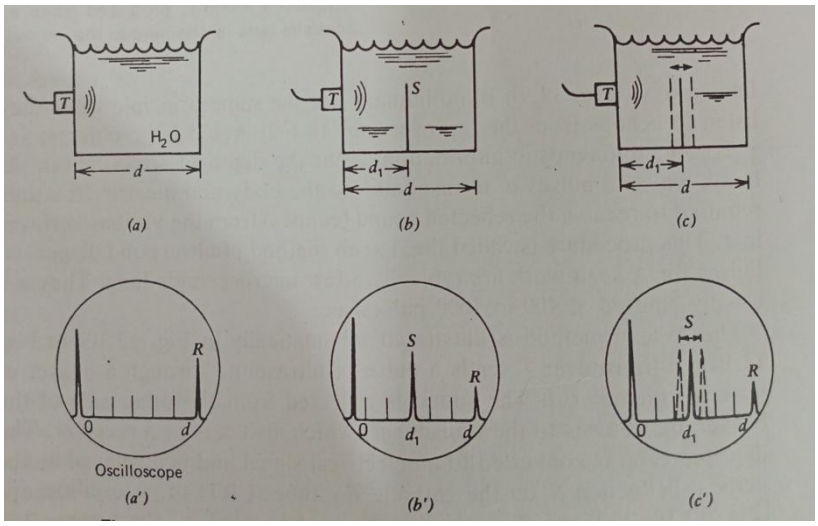



Figure 1

## B scan

For many clinical purposes A scans have been largely replaced by B scans. The B scan method is used to obtain two-dimensional views of parts of the body. The principles are the same as for the A scan expect that the transducer is moved. As a result each echo produces a dot on the oscilloscope at a position corresponding to the location of the reflecting surface (Fig. 2).

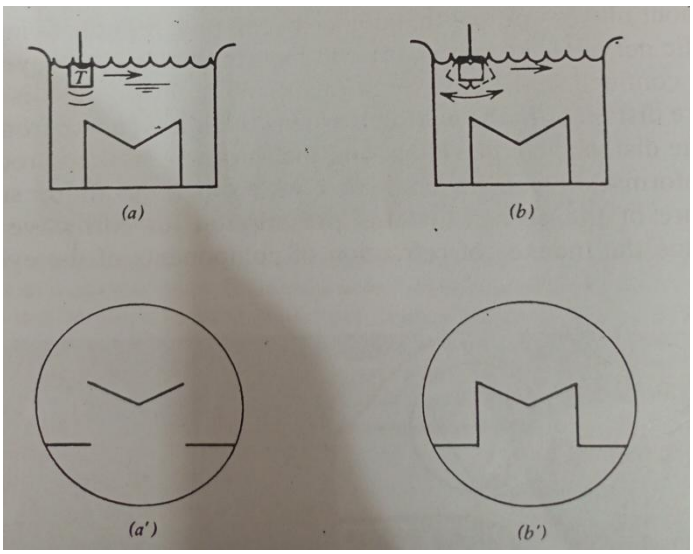



Figure 2

## M-scan

Method is used to obtain information about motion in the body with ultrasound; the M (motion) scan, which is used to study motion such as that of the heart and the heart valves.

The M scan combines certain features of the A scan and the B scan. The transducer is held stationary as in the A scan and the echoes appear as dots as in the B scan.

Figure 3a shows a transducer fixed at one position emitting a pulse of ultrasound into a beaker of water that a vibrating interface in it. Figure 3 b is a standard B scan showing the motion of the interface on the oscilloscope screen. When the oscilloscope trace is made to move vertically as a function of time, the motion of the interface is displayed as an M scan as seem in Fig. 3c.

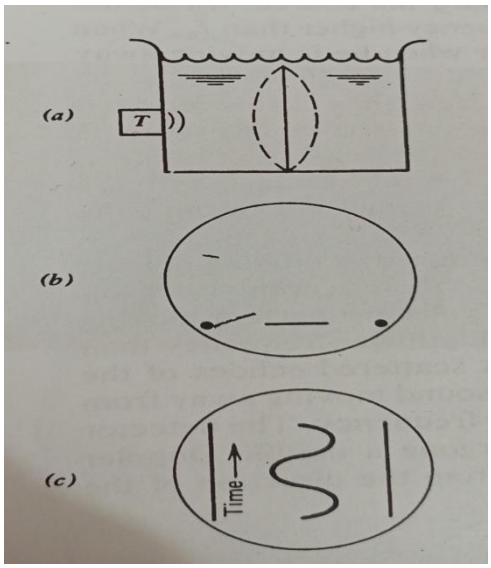



Figure 3

M scans are used to obtain diagnostic information about the heart. The places where the heart can be probed are quite limited because of poor ultrasound transmission through lung tissue and bone. The usual method is to put the transducer on the patient's left side, aim it between the ribs over the heart, and tip it at different angles to explore various regions of the heart (fig. 4). By moving the probe it is possible to obtain information about the behavior of a particular valve or section of the heart. The examiner must be familiar with the patterns of specific cardiac echoes to interpret the information. Several heart conditions can be diagnosed with M scans; we consider here M scans of mitral valves and M scans showing accumulation of fluid in the heart sac (pericardial effusion).

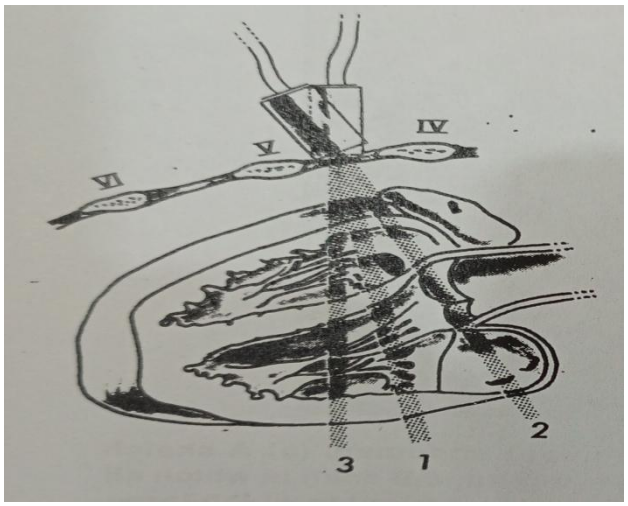



Figure 4

## Doppler effect

The Doppler effect can be used to measure the speed of moving objects or fluids within the body, such as the blood. When a continuous ultrasound beam is " received" by some red blood cells in an artery moving away from the source, the blood "hears" a slightly lower frequency than the original frequency $f_0$. The blood sends back scattered echoes of the sound it "hears," but since it is now a source of sound moving away from the detector, there is another shift to a still lower frequency. The detector receives a back-scattered signal that has undergone a double Doppler shift. When the blood is moving at an angle θ from the direction of the sound waves, the frequency change $f_d$ is

$$f_d = \frac{2f_\circ V}{v} cos\theta$$

Where $f_\circ$ is the frequency of the initial ultrasonic wave, V is the velocity of the blood, ν is the velocity of sound, and θ is the angle between V and ν (Fig. 5).

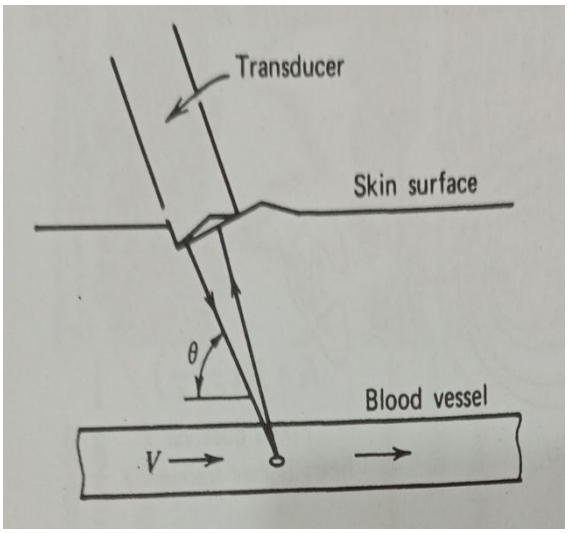



Figure 5

The Doppler effect is also used to detect motion of the fetal heart, umbilical cord, and placenta in order to establish fetal life during the 12-20 week period of gestation when radiological and clinical signs are unreliable. When a continuous sound wave of frequency $f_o$ is incident upon the fetal heart, the reflected sound is shifted to frequencies slightly higher than $f_o$ when the fetal heart is moving toward the source of sound and slightly lower than $f_o$ when the fetal heart is moving away from it. Variation in the frequency give the fetal heart rate. Figure 6 shows the instrument arrangement for monitoring the fetal heart. The output can be audible or displayed on an oscilloscope.

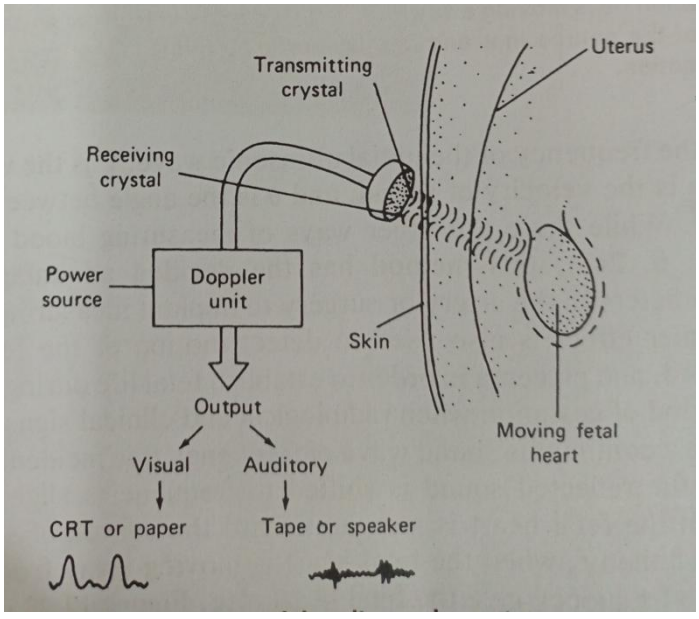



Figure 6

## Physiological effect of ultrasound in therapy

Various physical and chemical effects occur when ultrasonic waves pass through the body, and they can cause physiological effects. The magnitude of the physiological effects depends on the frequency and amplitude of the sound. At the very low intensity levels used for diagnostic work (0.01 W/cm$^2$ average power and 20 W/cm$^2$ peak power) on harmful effects have been observed. As the power is increased, ultrasound becomes useful in therapy. Ultrasound is used as a deep heating agent at continuous intensity levels of about 1 W/cm$^2$ and as a tissue-destroying agent at intensity levels of $10^3$ W/cm$^2$.

The primary physical effects produced by ultrasound are temperature increase and pressure variations. The primary effect used for therapy is the temperature rise due to the absorption of acoustic energy in the tissue.

In physical therapy the typical intensity is about 1-10 W/cm$^2$ and the frequency is about 1 MHz. Using Equation 1, we find that the amplitude of displacement A at 10 W/cm$^2$ in tissue is about $10^{-6}$ cm

$$\mathrm{I} = \frac{1}{2}\,\rho v A^2\,(2\pi f)^2 = \frac{1}{2} Z(A\omega)^2 \ldots\ldots\ldots\ldots (1)$$

Using Equation 2, we find that the maximum pressure amplitude $P_0$ is approximately 5 atm.

$$\mathrm{I} = \frac{P_o^2}{2Z} \ldots\ldots\ldots\ldots\ldots (2)$$

Recall that the change from maximum to minimum pressure occurs in a distance of one-half the wavelength; for a 1 MHz wave in tissue, $\lambda/2$=0.7 mm. Thus there is a substantial pressure change over a short distance. A beam of ultrasound with an intensity of 35 W/cm$^2$ can produce pressure changes of approximately 10 atmospheres! At very high frequencies, the energy can be passed to the molecules so quickly that it is impossible for the molecules to disperse the energy to the surrounding tissue through vibrations. The molecules can gain sufficient energy to break their chemical bonds. Intense ultrasound waves can change water into $H_2$ and $H_2O_2$ and rupture DNA molecules.

At power levels of $10^3$ W/cm$^2$ it is possible to selectively destroy tissue at a desired depth by using a focused ultrasound beam. Work on the brains of cats indicates that the mechanism for the destruction of tissue appears to be biochemical and not merely due to local heating.